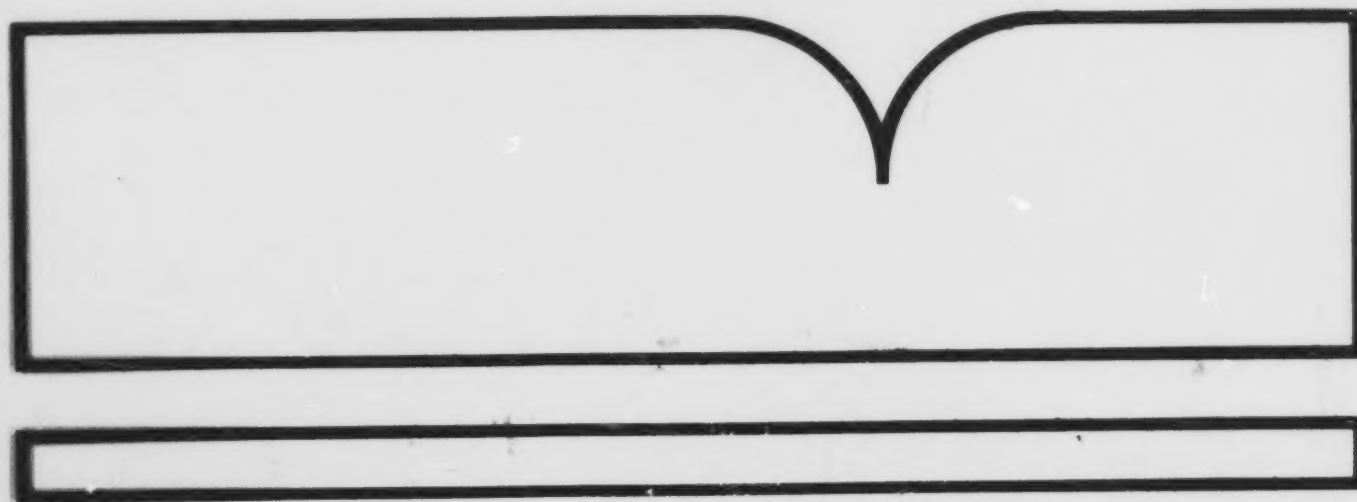


Effects of Toxicants on Plankton

(U.S.) Environmental Research Lab.
Gulf Breeze, FL

1982



U.S. Department of Commerce
National Technical Information Service

NTIS

PB83-117044

EPA-600/D-82-338
PUBLISHED PAPER

EFFECTS OF TOXICANTS ON PLANKTON¹

Gerald E. Walsh

U.S. Environmental Protection Agency
Environmental Research Laboratory
Gulf Breeze, Florida 32561

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA-600/D-82-338	2. PUBLISHED PAPER	3. RECIPIENT'S ACCESSION NO. PB83-117044
4. TITLE AND SUBTITLE EFFECTS OF TOXICANTS ON PLANKTON	5. REPORT DATE 1982	6. PERFORMING ORGANIZATION CODE
	8. PERFORMING ORGANIZATION REPORT NO.	
7. AUTHOR(S) Gerald E. Walsh	10. PROGRAM ELEMENT NO. ACBELA	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	11. CONTRACT/GRANT NO.	
	13. TYPE OF REPORT AND PERIOD COVERED	
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Environmental Research Laboratory Office of Research and Development Gulf Breeze, FL 32561	14. SPONSORING AGENCY CODE EPA/600/04	
	15. SUPPLEMENTARY NOTES Presented at the International Course on Environmental Toxicology, August 16-20, 1982, at Heriot-Watt University in Edinburgh, Scotland	
16. ABSTRACT Effects of heavy metals, pesticides, and industrial and municipal wastes on plankton in the field and laboratory are reviewed. Both holoplankton and meroplankton are discussed. In many cases, meroplanktonic stages of benthic species are more sensitive than adults although death or depression of physiological activities are often used as criteria for effects of pollutants with algae and animals, algae may be used to detect effects of growth stimulants.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS (This Report) unclassified	21. NO. OF PAGES 69
	20. SECURITY CLASS (This page) unclassified	22. PRICE

INTRODUCTION

Plankton and pollutants are ubiquitous in fresh and salt water in all parts of the earth. Since they occur together in natural aquatic systems, it is important that we understand their interactions and, when such interactions lead to undesirable situations, that we undertake measures to avoid or correct them. Although some field studies have been done, methods for detecting interactions that may be considered deleterious to aquatic systems are mainly laboratory tests of the toxicity of single compounds on single species in static or flowing water. Most researchers admit that these tests do not simulate environmental exposure, but do estimate the relative toxicity of each compound and data from them can be used to estimate potential environmental impact.

Environmental impact assessment has been reviewed by Rosenberg et al. (1981), who included identification of main impacts, prediction of effects, formulation of usable recommendations, and monitoring as requirements. Toxicity testing relates to each of these elements and can be used to determine concentrations of toxicants considered to be safe in natural systems. Eaton (1973) described methods for estimation of safe concentrations of chemicals by use of acute and chronic toxicity tests with Daphnia magna and fishes, but his methods can be used for other species as well. Nemetz and Drechsler (1978) reviewed the role of effluent monitoring in environmental control, and Kohn (1980) discussed toxicity testing as a monitoring tool. Pearce (1980) pointed out that single species can be used to estimate the extent of pollution in selected areas, but effects of long-term environmental changes on marine and

¹ Contribution No. 430 from the Gulf Breeze Laboratory.

estuarine organisms must be assessed by monitoring over decades.

There are innumerable references to toxicity tests on freshwater, estuarine, and oceanic plankton in the scientific literature, but few demonstrate actual effects in natural systems. In this short review, I have chosen references that demonstrate effects of pollutants, address important aspects of pollution biology and toxicity testing, review some of the literature, and describe modern methods for testing and interpretation of data, on planktonic species.

DEFINITIONS OF TERMS

The following terms are used in this review:

Static Test - A toxicity test in water that is not changed or is not flowing.

Static Renewal Test - A toxicity test in which part of the exposure water is removed and an equal volume replaced at specific time intervals.

Flow-Through Test - A toxicity test in which contaminated water flows either intermittently or continuously through the exposure chamber.

LC50 - The calculated concentration of a toxicant that would cause death of 50 per cent of an exposed population.

EC50 - The calculated concentration of a toxicant that would affect, but not kill, 50 per cent of an exposed population.

SC20 - The calculated concentration of a substance that would stimulate growth of an algal population by 20 per cent.

ET50 - The calculated time required to kill 50 per cent of a population exposed to a specific concentration of a toxicant.

No Observed Effect Concentration - The highest concentration of a toxicant that has no effect in a toxicity test.

Median Tolerance Limit (TL_M) - The calculated concentration of a

toxicant in which 50 per cent of exposed organisms survive for a specified period of time.

Maximum Allowable Toxicant Concentration (MATC) - The concentration of a toxicant, calculated from long-term tests, that would not cause significant harm to an exposed population.

Application Factor - A number used to estimate concentration of a toxicant that will not cause significant harm to a population during chronic exposure. It is calculated from the expression.

$$\frac{\text{MATC}}{96\text{-h LC50}}$$

Bioconcentration - The process whereby living organisms acquire toxicants from water through gills or integument and store it in their bodies at concentrations higher than in the environment.

Bioconcentration Factor - The ratio of concentration of toxicant in an organism to its concentration in water.

Bioaccumulation - The process whereby living organism acquire and store a toxicant through bioconcentration, after ingesting it with food, or both.

Bioaccumulation Factor - The ratio of concentration of toxicant in an organism to its concentration in the food.

Biomagnification - The process by which bioaccumulated toxicants increase in concentration as they pass upward through two or more trophic levels.

Exposure Assessment - A process used to evaluate the concentration of a toxicant to which an organism, population, community, or ecosystem is exposed.

Hazard Assessment - A process used to evaluate the danger that a toxicant poses to an organism, population, community, or ecosystem.

EFFECTS OF TOXICANTS ON PLANKTON IN THE FIELD

It is often difficult to show that pollutants affect plankton in the field because recruitment occurs rapidly in areas affected by influx of water. Also, physical and chemical properties of toxicants can be modified by conditions that exist in water. For example, Harding and Vass (1979) used an experimental model to demonstrate rates of uptake and depuration of DDT by the euphausiid, Thysanoessa rachii, and the copepod, Calanus finmarchicus. After relating rates of uptake and depuration to concentrations in the organisms and seawater off Nova Scotia, the authors concluded that a considerable amount of DDT in seawater is bound to organic and inorganic particles and is thus unavailable to zooplankton through the water. Although Harding and Vass (1979) did not speculate on availability of other toxicants, they may also be bound to particles. It is possible that a variety of toxicants sorbed to particles when ingested become available to zooplankton in concentrated form if they can be removed from the particles and absorbed in the gut. In a later paper, Harding *et al.* (1981) demonstrated that C. finmarchicus retained between 60 and 70 per cent of DDT sorbed to Thalassiosira weissflogii when that alga was the only source of food. Dobroski and Epifanio (1980) fed Thalassiosira pseudonana that was contaminated with ^{14}C -benzo[a]pyrene to larvae of the hard clam, Mercenaria mercenaria, and concluded that uptake from water and by trophic transfer may be equally important to natural populations.

Plankton communities of enclosed bodies, such as ponds and lakes, may be more likely to demonstrate stress from pollutants than estuarine or oceanic species. Thus, Yan and Strus (1980) showed that species richness and biomass of crustacean zooplankton in lakes contaminated with acid waste and heavy metals were strongly reduced in comparison with nearby uncontaminated lakes.

Direct effects of pollutants are difficult to demonstrate in the sea. Glover et al. (1970), in a 21-year study, demonstrated declines in total numbers, zooplankton biomass, and population density of the copepods, C. finmarchicus, Calanus helgolandicus, Pseudocalanus sp., and Paracalanus sp., and the pteropod, Spiratella retroversa, in the North Sea and northeastern Atlantic Ocean. They speculated that pollution caused the declines. However, no changes were found in numbers of the copepod, Temora longicarpus, and the pteropod, Clione limacina, and numbers of the copepod, Acartia clausi, increased. In the absence of other data, proof of pollution effects could not be shown, and it is possible that the authors observed natural variability that occurs over relatively long periods of time.

Oil is a major source of pollutants in seawater. Forrester (1971) showed that, after the wreck of the tanker Arrow in Chedabucto Bay, Nova Scotia, oil particles with diameters between 0.01 and 0.1 mm were distributed uniformly in the water column. Conover (1971) stated that this size range includes most of the natural food of zooplankton. He reported that, three weeks after the spill, the copepods, Temora longicornis and Calanus finmarchicus, contained small particles of oil in the interstices of the feeding appendages, foregut and hindgut. Oil passed through the animals with no apparent harmful effects. Conover suggested that defecation of oil in fecal pellets, which are denser than seawater and thus sink to the bottom, is an important natural mechanism for oil dispersal. He also suggested that bacteria on fecal pellets accelerate the rate of degradation of oil at sea.

After the TSESIS oil spill off Sodertalje, Sweden, direct effects of oil on plankton were limited to decreased zooplankton biomass in the immediate vicinity of the tanker (NOAA, 1980).

Kuhnhold (1978) described plankton in the vicinity of the Argo Merchant oil spill near Nantucket Island, Massachusetts. Although only a few phytoplankton tows were made, abundance of major phytoplankton species from the spill area did not differ appreciably from an uncontaminated reference site. For zooplankton, lowest biomass and numbers were found within the oil slick. While such data are difficult to interpret because of the patchy distribution of zooplankton in the sea, pelagic crustaceans were found to be contaminated by oil. The copepod, Centropages typicus, and the amphipod, Gammarus annulatus, were contaminated externally, with oil coating the feeding appendages, carapace, and extremities. Also, oil adhered to walls of the stomach and gut and was eliminated in fecal pellets. Although these species are eaten by fish larvae, no effect of oil was found on fish. However, eggs of the cod, Gadus morhua, and the pollack, Pollachius virens, were heavily coated with oil, and the mitotic index indicated that mortality of eggs was greater than would be expected in an uncontaminated area.

Physiological responses of copepods to oil from the Amoco Cadiz spill near Aber Benoit were compared to the physiological state of copepods from a non-polluted area by Samain et al. (1980). The ratio of amylase to trypsin was calculated for copepods in the two areas for a year after the spill. The copepod, Anomalocera patersoni, was very sensitive, and the authors suggested that it would be a good species for biological tests with oil. Three periods of pollution effects, in which the amylase to trypsin ratio was depressed, were found: an immediate effect, for 15 days offshore and 30 days inshore, associated with high copepod mortality; a secondary effect for three months, at which time resettlement did not occur; and a tertiary effect for an additional nine months, when ratios were depressed due to chronic exposure to low concentrations of oil. Since high mortality of copepods occurred only within

the first month after the spill, ecological significance of reduced ratios remains obscure.

Since studies on direct effects of toxicants on plankton in completely natural systems cannot be controlled (see the discussion by Ignathiades and Mimicos, 1977, on difficulties in interpretation of field data), it is necessary to perform experiments in which at least some variables are controlled. An approach to this problem has been made by enclosing large volumes of seawater in various types of bags and subjecting the plankton to toxicant stress.

EFFECTS OF TOXICANTS IN PLANKTON IN FIELD ENCLOSURES

Enclosures that contain natural assemblages of plankton or selected species from the laboratory have been used to estimate effects of pollutants in the field. Although such enclosures, which range in size from small bags of dialysis tubing to very large containers made of nylon-reinforced polyethylene, may exclude important considerations, such as recruitment of new organisms, mixing, and availability of nutrients, it is generally thought that responses of plankton in them more closely mimic those in the field than do laboratory tests under less natural conditions. Studies with large systems are expensive, time-consuming, and impractical as routine toxicity tests on specific substances or complex wastes. Small dialysis bags placed in contaminated areas are useful in determining the extent of pollution in natural systems. A chamber composed of nitex screen and Plexiglas for use with small animals was described by O'Brien and Kettle (1981), and Marshall and Mellinger (1980) reported results with natural plankton and small enclosures.

Sakshaug and Jensen (1978) reviewed the principles involved in use of small enclosures with marine phytoplankton. They described how dialysis tubing with enclosed algae could be used for monitoring water quality and for

studying effects of pollutants on growth of phytoplankton. Cellular responses of laboratory-cultured algae in dialysis bags in the field were described by Maestrini and Kossut (1981). During adjustment to equilibrium in the field, Skeletonema sp., Hemiselmis viresens, Platymonas suecica, and Phaeodactylum tricornutum lost phosphorus, ATP, nitrogen, and chlorophyll a from the cells. Five cell divisions were required before equilibrium was attained. Marsot et al. (1981) described an improved method for dialysis culture that could be used for studies on toxicants. The relatively complicated and large-scale system, which required recirculation of growth medium, yields algal biomass similar to that in laboratory batch culture.

Three species of marine unicellular algae, P. tricornutum, S. costatum, and Thalassiosira pseudonana, were exposed to water of two Norwegian fjords that were polluted by heavy metals (Eide et al., 1979). The authors demonstrated uptake of copper, zinc, cadmium, and mercury from the natural water by P. tricornutum. The three algal species responded differently to the polluted waters: S. costatum was the most sensitive species, its population growth being inhibited completely; population growth rate of T. pseudonana was slowed in one fjord and completely inhibited in another; and population growth of P. tricornutum was normal in one fjord and reduced in another. These studies demonstrated that concentrations of metals in the fjords were high enough to kill or inhibit growth of sensitive algal species.

Kuiper (1981) exposed natural populations of phytoplankton to mercuric chloride in plastic bags attached to a raft. A single dose of 0.5 $\mu\text{g/L}$ altered the species composition, with a shift to predominance of species of large size, probably because mercury reduced the number of small zooplankton herbivores. At 5 $\mu\text{g/L}$ and above, mercury inhibited growth: the peak in algal biomass was delayed nine days by 5 $\mu\text{g/L}$ and complete inhibition of growth was caused

by 50 $\mu\text{g/l}$.

Klotz (1981) cultured three species of freshwater algae, Chlamydomonas sp., Scenedesmus sp., and Chlorella sp., in dialysis tubing in a river polluted with copper. No effect of copper on growth was demonstrated, but accumulation of the metal occurred. Conversely, Sanders et al. (1981) reported significant decline in biomass of natural communities of phytoplankton when exposed to copper and chlorine in seawater in small tanks.

For a review of the use of larger enclosed systems, the book edited by Grice and Reeve (1982) contains 30 chapters that discuss many aspects of this important subject.

EFFECTS OF TOXICANTS ON PHYTOPLANKTON IN LABORATORY STUDIES

Marine and freshwater unicellular algae have been used for many years in studies on bioactivity of single compounds and mixed wastes. The most commonly-measured responses of unialgal cultures to pollutants are growth inhibition and growth stimulation of populations. Reports in recent years, however, have included descriptions of effects on morphology, physiology, and interactions among populations. Walsh (in press a) reviewed principles, methods, and problems of algal toxicity tests and described responses of algae to industrial and municipal wastes. He concluded that algae were generally more sensitive to such wastes than animals because population growth was stimulated or inhibited at concentrations lower than those required to kill animals. Conversely, algae were generally less sensitive than animals to single toxicants. See Walsh et al. (in press a) for additional information on comparison of algal and animal responses to complex industrial wastes.

Oil

Effects of oil on phytoplankton have been reviewed extensively by Corner (1978). See also AIBS (1978) for a review of oil and its physical, chemical,

and biological effects in seawater.

Crude oil and petroleum products are mixtures of hydrocarbons that are soluble in water or that volatilize from the surface, and each compound may exert a distinctive toxic effect. A major problem associated with testing effects of oil on algae is related to loss of hydrocarbons over the time-course of the experiment. Studies have been done on crude oils, their water-soluble fractions, and individual components. Boylan and Tripp (1971) and Anderson et al. (1974) showed that bicyclic and tricyclic aromatic hydrocarbons of the water-soluble fraction are responsible for most of the toxicity of crude and fuel oils in short-term tests.

Oil can affect population growth rates of algal cultures (Mironov and Lanskaya, 1966; Gordon and Prouse, 1973; Pulich et al., 1974; Soto et al., 1975 a, b; Dunstan et al., 1975; Kauss and Hutchinson, 1975; Parsons et al., 1976; Batterton et al., 1978; Hsiao, 1978). Growth may be inhibited or enhanced, depending upon concentration of oil and algal species tested. Gaur and Kumar (1981) exposed Anacystis nidulans, Chlorella vulgaris, Selenastrum capricornutum, and Oocystis sp. to three crude oils and a furnace oil, and demonstrated growth inhibition of all species. Furnace oil was the most toxic oil and S. capricornutum, the most sensitive species. Corner (1978) reviewed the literature on mechanisms of toxicity of oils to phytoplankton and cited alterations in cell membrane permeability and inhibition of enzyme systems, photosynthesis, and nucleic acid synthesis as responses to oil.

Pulich et al. (1974) compared responses of Thalassiosira pseudonana, Agmenellum quadruplicatum, Nostoc sp., Dunaliella tertiolecta, Chlorella vulgaris, and Gymnodinium hallii to crude oil. Growth of C. vulgaris was severely inhibited by water soluble components of the low-boiling fraction. Thalassiosira pseudonana and A. quadruplicatum did not respond to those

components, but were sensitive to water soluble extracts of high-boiling fractions. On the other hand, No. 2 fuel oil at up to 7.5 mg/L had no effect on population growth of these species.

Other responses to oil are lengthened lag phase (Pulich et al., 1974), increased growth rate (Dunstan et al., 1975), and decrease in cellular protein and carbohydrate (Soto et al., 1975 b).

Mechanisms of toxicity of the water-soluble fraction of No. 2 crude oil, Southern Louisiana crude, and Kuwait crude were reported by Armstrong et al. (1976). The authors reported extended lag phase and growth inhibition due to the water soluble fraction and 1-methylnaphthalene. After analyzing effects upon oxygen production, ATP concentration, alkaline phosphatase and phosphodiesterase activities, and protein in cell extracts and enzyme preparations, it was concluded that the toxic mechanisms of petroleum hydrocarbons to unicellular algae are: 1) an immediate inhibition of electron transport systems or uncoupling of phosphorylation, or both and 2) long-term growth inhibition that may be caused by hydrocarbon uptake into membranes.

Heavy Metals

Effects of heavy metals on phytoplankton have been reviewed extensively by Davies (1978). Although some metals (Cu, Zn, Co, Mn, Mo, and Fe) are essential for algal growth and development, these and others (notably Hg, Cd, Ag, Ni, Pb, Se, Cr, and As) may be toxic at concentrations higher than those normally found in natural systems. Thus, Subba Rao (1981 a) showed that population growth, measured as the maximum rate of cell division in the medium of Guillard and Ryther (1962), was affected strongly by concentrations of a mixture of heavy metals. Treated algae fell into three categories: a direct correlation between growth rate and concentration was shown by Dunaliella tertiolecta, Chaetoceros septentrionalis, Thalassiosira spp., and Rhizosolenia sp.; no

effect of metals concentration was found with Phaeodactylum tricornutum; and an inverse correlation between growth rates and concentration was exhibited by Skeletonema costatum, an unnamed centric diatom, and natural phytoplankton. Subba Rao (1981 a) also reviewed the role of organic chelators in toxicity of heavy metals to phytoplankton. For effects of heavy metals on growth and photosynthesis of algae, see Malanchuck and Gruendling (1973), Silverberg et al. (1977), Bently-Mowat and Reid (1977), Hart and Scaife (1977), Stewart (1977), Fezy et al. (1979), Stratton and Corke (1979), Truhaut et al. (1980), Huisman et al. (1980), Spencer and Greene (1981), Subba Rao (1981 a,b), Wilkfors and Ukeles (1982) and Stillwell and Corum (1982). For effects of temperature, pH, phosphate, organics, and density of the algal culture on toxicity of metals, see also Knowles and Zingmark (1978), Chan et al. (1981), Gipps and Collier (1980), and Huisman et al. (1980). Rai et al. (1981) suggested that alkaline and hard eutrophic waters protect freshwater organisms against heavy metal toxicity.

Metals may act synergistically, antagonistically, or additively with one another. Combinations of zinc and cadmium acted synergistically on S. costatum, but antagonistically on P. tricornutum (Braek et al., 1980). Also, sorption of the metals was dependent on the magnesium content of the medium. Hart et al. (1979) reported that manganese inhibited cadmium uptake by Chlorella pyrenoidosa and concluded that manganese and cadmium share a common transport system. Stratton and Corke (1979) reported antagonistic behavior of mercury, cadmium, and nickel with Anabaena inaequalis and proposed that the metals competed for cellular binding sites.

The influence physical factors can have on toxicity in laboratory tests was demonstrated by Roderer (1980, 1981) with tetraethyl lead. The compound was not toxic to the crysophycean flagellate, Poteriochromonas malhemensis,

in darkness, but population growth, mitosis, and cytokinesis were inhibited in the light. It was found that the parent compound was not toxic, but photolytic processes caused formation of triethyl lead, a highly toxic compound. Roderer (1981) reported that inorganic lead was the least toxic derivative of tetraethyl lead to P. malhemensis, but Hessler (1974) and Woolery and Lewin (1976) found toxic effects on viability and motility of Platymonas subcordiformis and on respiration and photosynthesis of P. tricornutum at concentrations as low as 2.5 and 0.1 mg Pb/L, respectively.

Although algae generally are not affected strongly by concentrations of heavy metals in the field, they do accumulate some of them and may transfer them to higher trophic levels. Davies (1973) stated that, in phytoplankton, heavy metals appear to be accumulated by ion-exchange processes that involve organic molecules and that the process is governed by the rate of diffusion across the cell membrane. In the diatom, P. tricornutum, he suggested that, after rapid absorption at the cell surface, zinc diffuses through the cell membrane and is adsorbed at ion-exchange sites within the cell. Accumulation of cadmium by D. tertiolecta occurred in two phases (Jennings and Rainbow, 1979). The first phase, which consisted of rapid, linear uptake related directly to concentration of cadmium in the medium, was followed by a phase of stabilization, with the concentration factor of 1350, which was not dependent on concentration in the medium. Li (1980) also studied uptake of cadmium by Isochrysis galbana and reported that, after initial inhibition of growth, the alga recovered and grew normally. Recovery did not appear to be due to either loss of cadmium from the medium or development of an exclusion mechanism by the cells. Rather, Li postulated that acquisition of tolerance was due to changes in cytosolic distribution of the metal, mainly increased binding to a cytosolic moiety of low molecular weight. Fujita et al. (1977) showed that mercury was

found mainly in the chloroplasts and soluble fractions of Synedra ulna, with initial concentration in the chloroplasts and later transfer to soluble fractions. When dead cells were exposed to mercury, none was found in any fraction. Macka et al. (1979) described passive uptake of cadmium and mercury by living and dead cells of Chlamydomonas reinhardi, and stated that uptake by dead cells was by adsorption to cell walls.

Ribeyre et al. (1981) and Boudou and Riberye (1981) demonstrated trophic transfer of mercury from the alga C. vulgaris to the daphnid Daphnia magna. When the alga was contaminated with mercuric chloride, very little metal was transferred to D. magna. However, when contaminated with methyl mercuric chloride and fed to the daphnid, approximately 20 per cent of the mercury on the alga was transferred at 10°C and approximately 60 per cent was transferred at 18°C. The authors concluded that large amounts of the methylated form of mercury can be transferred through food chains. Field studies, however, show that mercury is often in high concentration in algae, but in low concentration in higher trophic levels (Baeyens et al., 1979; Gachter and Geiger, 1979).

All metals do not behave in trophic transfer as does mercury. Amiard and Amiard-Triquet (1975) described substantial transfer of cobalt in a food chain that consisted of the diatom, Navicula sp. (producer), the lamellibranch mollusc, Scrobicularia plana (primary consumer), and the crab, Carcinus maenas (secondary consumer). Amiard-Triquet (1979) demonstrated trophic transfer of cobalt through a fresh water food chain composed of Chlorella sp., D. magna, and the carp, Cyprinus carpio. Although the transfer factor between trophic levels was low, uptake by the alga was so great that transfer of cobalt through the chain accounted for more cobalt in the crustacean and fish than did direct uptake from water.

Heavy metals in algae may also affect survival and development of animal larvae. Wilkfors and Ukeles (1982) fed algae contaminated with copper, cadmium, or zinc to veliger larvae of the American oyster, Crassostrea virginica, and noted poor growth and high mortality of the larvae. They concluded that pollution of estuarine waters by heavy metals could decrease rates of primary productivity by algae and that remaining algae would be potentially toxic to grazing animals. Walsh et al. (1977) concluded that accumulation of toxicants by algae with subsequent transfer to higher trophic levels is more important in natural systems than direct effects of toxicants on the algae.

Cell morphology is often affected by heavy metals. Saboski (1977) described effects of mercury and tin on frustular ultrastructure of Nitzschia liebetrutti. A high rate of abnormal morphology was caused by each metal at 1.5 $\mu\text{g-at/L}$. Cadmium induced increase in filament length and loss of cellular contents in A. inaequalis (Stratton and Corke, 1979). Thomas et al. (1980) demonstrated effects of six metals on morphology of Thalassiosira aestivalis. Cadmium, mercury, and lead interfered with cell division and caused disruption of cell separation, clumping, and formation of elongated, bent, and out-of-column cells. Cooper, zinc, and germanium affected silicon metabolism, increased chain length, inhibited normal separation of cells, and stopped formation of the central chitinous threads that separate normal cells. Fisher and Jones (1981 a) reported that cells treated with copper appeared indistinguishable from silicon-limited cells in copper-free medium. Fisher and Jones (1981 b) compared the sublethal effects of mercury, copper, zinc, lead, cadmium, and manganese and related them to solubility products of the metal sulfides. They suggested a common action of the six metals - binding to sulfhydryl-containing compounds in the cell. Such binding would affect

numerous metabolic processes, including those that regulate silica deposition in diatoms.

Pesticides

Effects of pesticides on algae are similar to effects of heavy metals, i.e., death, inhibition of population growth, change in cell morphology or physiology, etc. For reviews of effects on algal population growth, see Walsh (1972, 1978) and Ware (1980).

Several factors confound results with algae. Laboratory clones respond differently to pollutants. For example, Fisher (1977) demonstrated intraspecific differences in response to toxic chemicals among clones from the Sargasso Sea and temperate zone estuaries. Growth of clones from the estuaries was less affected than growth of clones from the open ocean. Fisher (1977) suggested that clones from the less stable estuarine environment may have been more resistant because their membrane systems were adapted to environmental perturbation and prevented toxicants from entering the cells.

Pesticides are usually very poorly soluble in water, and it is often necessary to dissolve them in solvent carriers before adding them to cultures. Solvent carriers may themselves be toxic or they may affect toxicity of pesticides, and it is necessary to use adequate solvent controls in exposure systems. Majewski et al. (1978), Stratton et al. (1980), and Stratton and Corke (1981 a) showed that the commonly-used carrier, acetone, can react additively, synergistically, or antagonistically with pesticides and suggested that the effects may be due to cell membrane damage.

Algal cell size may be affected by pesticides, so that enumeration of cells may not give an accurate account of effect. Powers et al. (1977) showed that, whereas DDT had no effect on cell size of the marine dinoflagellate Exuviella baltica, a very low concentration (10 parts per billion) of dieldrin

caused disintegration of cells, inhibition of the growth rate, and diminution of size of surviving cells. Surviving cells averaged 11.2 per cent smaller than unexposed cells, and smaller size persisted for four generations after removal to dieldrin-free medium. Later, Biggs et al. (1978) found that 5 μ g of a polychlorinated biphenyl/L caused a shift in dominance within an estuarine algal community in dialysis culture from large centric diatoms to smaller pennate diatoms and microflagellates.

The presence of one algal species can affect toxicity of pesticides to another species. Fisher et al. (1974) found that toxicity of polychlorinated biphenyls to the diatom, I. pseudonana, was greatest when Chaetoceros sp. and S. costatum were present. Conversely, Walsh and Alexander (1980) showed that resistant species can protect sensitive species from pesticidal effects. When grown singly in the presence of 15 μ g/L of the herbicide, neburon, population growth of the red alga, Porphyridium cruentum, and the green alga, Neochloris sp., was strongly inhibited. When the diatom, Nitzschia angularum, a relatively resistant species, was present, growth was less restricted.

Results of growth tests with algae may be misleading because EC50 concentrations are indications of effect on growth rates and population size, not mortality. Walsh (in press b) showed that mortality of S. costatum at the ED50 concentration of five pesticides was negligible. After three days of exposure to an amidinohydrazone insecticide, growth rates were equal to that of the control, even though growth was inhibited severely for the first two days. Walsh (in press a) discussed the limitations of algal growth tests, and Payne and Hall (1979) gave a method for detecting whether a compound is algicidal or algistatic.

Industrial and Municipal Wastes

Whole industrial and municipal wastes are mixtures of numerous organic

and inorganic substances. Phytoplankton are good indicators of pollution by these complex wastes because they respond to growth stimulants and inhibitors. Walsh and Alexander (1980) and Walsh et al. (1980) demonstrated that concentrations as low as 0.5 per cent may stimulate growth by 20 per cent (SC20) in 96 hours. Stimulation of growth at low concentrations and inhibition of growth at higher concentrations was common. The subject of effects of industrial and municipal wastes on phytoplankton was reviewed by Walsh (in press a), and Walsh et al. (1982) described effects of industrial wastes on algae and crustaceans.

EFFECTS OF TOXICANTS ON ADULT ZOOPLANKTON

Crustaceans comprise the largest taxonomic group in the holoplankton, and most work on the holoplankton has been done on adults. Dawson (1979) has reviewed effects of various pollutants on copepods, and publications reviewed by him will not be discussed here. Nimmo et al. (1977) stated that the mysid, Mysidopsis bahia, is a sensitive member of the estuarine holoplankton and described methods for its use in acute and chronic tests.

Oil

As with algae, the various fractions of oil have different effects on holoplankton. Weathered No. 2 fuel oil was more toxic to the planktonic shrimp, Lucifer faxoni, than fresh oil after exposure for 48 hours (Lee et al., 1978). The authors measured effects on survival, respiration, feeding rate, and degree of activity and concluded that volatile components were important in toxicity after spillage of oil. Alkyl benzenes, indans, and naphthalenes were associated with acute toxicity, but were lost by volatilization from test medium within 24 hours. Less toxic components, such as alkyl anilines, phenols, and indoles, were less volatile and were present at greater than 50 per cent initial concentrations after 5 days in seawater.

Spooner and Corkett (1979) reported sub-lethal toxicity of Kuwait oils to four species of marine copepods and their recovery after 20 hours of exposure. Feeding rates, as measured by fecal pellet production, were only slightly affected by 1 and 2 mg/L, and strong effects were not noted until exposure concentration reached 10 mg/L. Contrary to the results of Lee *et al.* with L. faxoni, the copepods survived and recovered well from exposure to weathered oil. Oil emulsified with detergents was not more toxic than oil alone.

The important role of fecal pellets in sedimentation of polycyclic aromatic hydrocarbons was described by Prah1 and Carpenter (1979), who showed that fecal pellets in Dabob Bay, Washington, controlled the rate at which those compounds were transferred to bottom sediments.

The mysid, Mysidopsis bahia, was more sensitive to simulated refinery effluent than grass shrimp, Palaemonetes pugio, the sheepshead minnow, Cyprinodon variegatus, and 17 freshwater organisms (Buikema *et al.*, 1981). The 96-h LC50 for M. bahia was 4.7 per cent. Chronic exposure to 2.7 per cent of the simulated effluent caused inhibition of growth and reproductive impairment. The most toxic component was fuel oil.

Heavy Metals

A large amount of research has been done on effects of heavy metals on marine and freshwater planktonic crustaceans. Winner (1981) gave typical survivorship curves for Daphnia magna exposed to heavy metals and showed that cadmium (80 µg/L) and zinc (300 µg/L) reduced body length, but had no effect on brood size. With regard to effects of copper, Winner *et al.* (1977) showed that nutritional stress upon D. magna affected acute, but not chronic toxicity. Effects of 21 metals on survival and reproduction of D. magna were reported by Biesinger and Christensen (1972). Cadmium, mercury, and cobalt were the most toxic to survival (48-h LC50) and reproduction; magnesium, calcium, and sodium

were least toxic. Weight of D. magna was reduced at metal concentrations that permitted survival, but impaired reproduction. Exposure of Daphnia pulex to concentrations as low as 5 µg cadmium/L caused reduction in the percentage of adults that produced young, the number of broods per adult, the number of young per brood, the number of progeny per adult, the intrinsic rate of natural increase, and the mean generation time (Bertram and Hart, 1979). Average longevity of D. pulex was not affected by 1 µg cadmium/L, but it was reduced in a concentration dependent manner between 5 and 30 µg cadmium/L.

Arnott and Ahsanullah (1979) reported that three species of marine copepods varied in their responses to copper, cadmium, and zinc. Scutellidium sp. was more sensitive to each metal than Paracalanus parvus and Acartia simplex in acute, 24-h tests. Copper was the most toxic metal, and cadmium was more toxic than zinc to two of the species. In addition to toxicity test data, the authors discussed problems associated with use of acute toxicity data for calculation of application factors and stated that the factors may be unrealistically high when such data are used.

Schultz et al. (1980) reported toxicity of selenium to D. pulex juveniles (48-h LC50=0.6 mg/L, 96-h LC50=0.1 mg/L) and adults (48-h LC50=1.3 mg/L, 96-h LC50=0.5 mg/L). The metal was most concentrated in cytoplasm and to a lesser degree in the nucleolus. Ultrastructural damage to mitochondria occurred after 16 hours of exposure. Uptake of selenium by unfed adults was rapid, reaching a maximum in about 12 hours. Uptake was slower when animals were fed, with maximum body concentration at 96 hours. Depuration was slow in fed and unfed animals.

Sublethal concentrations of cadmium were shown by Griffiths (1980) to cause morphological and ultrastructural abnormalities in D. magna. When

exposed to concentrations as low as 12 $\mu\text{g/L}$, gut diverticula became shrunken, empty of chlorophyll, and paralyzed. The author suggested that the responses were caused by an osmotic effect that resulted from a change in calcium metabolism and suggested that abnormalities may be used to monitor for effects of cadmium in the field.

In an experimental study of trophic transfer of lead, Vighi (1981) observed strong uptake by Selenastrum capricornutum, with concentration factors as high as 100×10^3 . When exposed algae were fed to D. magna, the crustacean accumulated lead. The author concluded that transfer from algae to Daphnia is the principal pathway for lead accumulation. In a similar study with marine species, Hatakeyama and Yasuno (1981 a) exposed the green alga, Chlorella sp., to cadmium and fed the contaminated algae to the cladoceran, Moina macrocopa. Chlorella exposed for six days to 0.02, 0.1, and 0.5 mg/L accumulated approximately 14, 70, and 300 μg cadmium/g respectively, in dry weight of cells. No effect was found when M. macrocopa fed on algae with the lowest concentration. Slight reproductive impairment occurred when algae with 70 $\mu\text{g/g}$ were ingested. Survival, growth rate, and rate of reproduction were strongly inhibited by the highest concentration. Rate of accumulation of cadmium from Chlorella was much slower than concentration from water.

Cadmium was acutely toxic to M. macrocopa and caused smaller brood size and number of broods (Hatakeyama and Yasuno, 1981 b). The 48-h LC50 was 71 $\mu\text{g/l}$ and the 72-h LC50 was 28 $\mu\text{g/L}$, and both the number of young and the number of broods produced were decreased to near zero by 1.6 μg cadmium/L. Delay in the formation of brood pouches and release of young by M. bahia were caused by 6.4 μg cadmium/L (Nimmo et al., 1977).

Toxicity of a heavy metal is related to its chemical form (Brown and Ahsanullah, 1971). Cunningham and Grosch (1978) compared effects of mercuric chloride and methyl mercury chloride for effects on mortality and reproductive performance of brine shrimp, Artemia salina. Significant reduction in adult lifespan was caused by 10 μg mercuric chloride/L and 5 μg methyl mercury chloride/L. Survival of nauplii produced by treated parents was not reduced by mercuric chloride, but significant reduction was caused by 1 μg methyl mercury chloride/L. Pairs exposed to more than 2 μg methyl mercury chloride/L did not produce nauplii. Results of reciprocal-cross experiments suggested that the female parent was more physiologically stressed than the male after exposure to 1 or 2 μg methyl mercury chloride/L.

Spehar et al. (1980) exposed D. magna to four arsenic compounds, arsenic trioxide, arsenic pentoxide, sodium diethyl arsenate, and sodium methyl arsenate, for 21 days in a flow-through test. None affected survival at up to 1 mg/L, but that concentration of arsenic trioxide caused cessation of production of young.

Pesticides

Responses of holoplakton to pesticides are similar to those to heavy metals, i.e., death, reduced fecundity, bioconcentration, bioaccumulation, etc. See Linden et al. (1979) for effects of numerous compounds on the harpacticoid copepod, Nitroca spinips. Effects of pesticides on zooplankton have been reviewed by Walsh (1978) and Ware (1980). Nimmo (in press) contains an extensive review of effects of pesticides. Isensee and Yoakum (1980) gave a method for exposure of D. magna to pesticides in microecosystems. Daphnia magna was sensitive to pentachloronitrohexane, simazine, trifluralin, dieldrin, and parathion.

It is not surprising that D. magna was sensitive to the insecticides because insecticides are designed to kill arthropods, but herbicides also affect zooplankton. They can kill or have less dramatic effects such as shown by Pott (1980) who reported that atrazine reduced the rate of food consumption by D. pulex. Atrazine also affected survival, growth, mean carbon content, and number of young produced by D. pulex after exposure for 28 days (Schober and Lampert, 1976; 1977). All responses were related directly to herbicide concentrations up to 20 mg/L.

Insecticidal effect may be affected by conditions of the environment. Stratton and Corke (1981 b) showed that, when particles such as algae, bacteria, and silica powder were in the water column, the insecticide permethrin induced their adhesion to setate appendages of D. magna. Adhesion to the appendages caused immobilization of the daphnid and significantly earlier death. Algal adhesion to appendages also occurred, to various degrees, upon exposure to diazinon, cypermethrin, methoxychlor, and carbaryl.

Relatively few non-arthropod zooplankters have been tested with pesticides, but fish embryos and fry have been shown to react to them (Macek and Sleight, 1977; Birge et al., 1979; Ward and Parrish, 1980; see also the next section).

Ware (1980) has pointed out that the predominant types of pesticides used have changed in the past 15 years from chlorinated hydrocarbons to carbamates and organophosphates, that kill directly, to insect growth regulators, such as methoprene and diflubenzuron, which may not kill immediately or directly, and to highly toxic synthetic pyrethroids. Miura and Takahashi (1973) stated that methoprene had no effect on copepods or cladocerans of a natural pond. However, copepods and cladocerans of a farm pond were killed by diflubenzuron (Apperson et al., 1978). Nimmo et al. (1980) reported that diflubenzuron,

which inhibits chitin synthesis, was acutely and chronically toxic to M. bahia. The 96-hour LC50 was 2.1 $\mu\text{g/L}$, and the 21-day LC50 was 1.2 $\mu\text{g/L}$. Exposure for 28 days to 0.075 $\mu\text{g/L}$ caused reduction in the number of young produced per female. Offspring of exposed females produced fewer young than controls, even though they themselves were not exposed, and Nimmo et al. (1980) expressed concern that compounds such as diflubenzuron affect larval and juvenile stages of non-target crustaceans. Nimmo et al. (1981) compared survival, growth, and reproductive responses of M. bahia and other estuarine organisms to 11 pesticides and gave the MATC and application factor for each. They concluded that acute test data for pesticides can be used to predict effects of chronic exposure.

The importance of microcrustaceans in bioaccumulation, bioconcentration, and biomagnification was demonstrated for marine species by Harding and Vass (1979) and Harding et al. (1981), and for freshwater microcrustaceans by Khan and Khan (1974). Euphausiids, Thysanoessa raschii, were used by Harding and Vass (1979) to determine uptake constants for DDT and to demonstrate that a large amount of DDT is bound to particles and thus unavailable in the soluble form to plankters. In a later study, Harding et al. (1981) showed that the copepod, Calanus finmarchicus, retained 60 to 70 per cent of DDT adsorbed to the alga, Thalassiosira weissflogii, after ingestion and concluded that direct uptake of the pesticide from seawater was not required to achieve DDT concentrations found in copepods from the field. Khan and Khan (1974) demonstrated the importance of bioconcentration by small crustaceans (Simocephalus vetulus and Daphnia sp.) to biological magnification of chlorinated hydrocarbons in food chains.

Industrial and Municipal Wastes

Herbes and Risi (1978) showed that the polycyclic aromatic hydrocarbon,

anthracene, was accumulated rapidly from water by D. pulex. When the initial concentration of anthracene in exposure water was 0.02 µg/L, equilibrium between D. pulex and water was reached in approximately six hours, and the concentration factor was 760. When transferred to clean water, 30 to 35 per cent of the total body burden was released in ten minutes and all was depurated within 20 hours.

A comparative study of 13 homologous linear alkyl sulfonates and D. magna and D. pulex was reported by Maki and Bishop (1979). There were no differences in response of either species as estimated by 48-hour LC50 values, but there were increases of up to one order of magnitude in toxicity for each increase of two alkyl carbons: LC50 for a 10-carbon compound was 29.6 mg/L, whereas for an 18-carbon compound, it was 0.12 mg/L.

The most sensitive criteria for estimation of the no-observed-effect concentration for acridine and D. magna were the total number of young produced per female, the number of broods produced per female, and the number of young per brood (Parkhurst et al., 1981). Whereas the 48-hour LC50 for the first instar was 2.3 mg/L, the no-observed-effect concentration for these responses was 0.4 mg/L.

Phthalate esters are common in industrial and municipal wastes. Sanders et al. (1973) exposed D. magna to 3, 10, and 30 µg/L of di-2-ethylhexyl phthalate for a complete life cycle (21 days) and reported that total production of offspring was inhibited by 50, 70, and 83 per cent in the three concentrations, respectively.

Halogen compounds occur frequently in industrial and municipal wastes. Capuzzo (1979) reported that after exposure of the rotifer, Brachionus plicatilis, for only 30 minutes, the LC50 for free chlorine was 1.2 mg/L and for chloramine was 0.35 mg/L. Rotifers that survived exposure to either

toxicant had significantly lower filtration rates and egg production rates than control animals and reduced reproduction rates were not sustained by the second generation. Capuzzo (1979) concluded that exposure to free chlorine or chloramine did not cause permanent alteration of the reproductive potential of rotifer populations. There was a direct relationship between toxicity of chlorine and temperature to the opossum shrimp, Neomysis americana, (Margrey et al., 1981) and growth of A. salina was inhibited significantly by the sublethal concentration of 5 mg fluorine/L (Pankhurst et al., 1980).

When exposed to complex whole wastes from textile mills, D. pulex was more sensitive than the grass shrimp, Palaemonetes pugio, the sheepshead minnow, Cyprinodon variegatus, and the fathead minnow, Pimephales promelus, (Walsh et al., 1980).

EFFECTS OF TOXICANTS ON EGGS, EMBRYOS, AND YOUNG

In many cases, embryos, larvae, and fry that occur in the meroplankton are more sensitive than adults. McKim (1977) reviewed effects of 34 organic and inorganic chemicals on fishes and concluded that embryos, larvae, and juveniles were generally the most sensitive stages. Birge et al. (1974, 1979) reviewed effects of toxicants on eggs of fishes and amphibians. Macek and Sleight (1977) tested the hypothesis that concentrations of toxicant safe to fish over their entire life cycles can be estimated from results of continuous exposure of embryos and newly hatched fry. Their assumptions were: (a) the chemical does not exhibit significant accumulative toxicity, (b) there is a single mode of action through which the effect of the chemical is manifested in a relatively short period of time, and (c) the effect is most severe on embryos and fry. The authors presented data on pesticides and heavy metals showing that the hypothesis was valid and that, in most cases, estimation of specific application factors derived from data on critical life stages approximated

specific applications factors derived empirically from chronic toxicity studies.

The concept of Macek and Sleight (1977) can also be applied to invertebrate species in which embryos and larvae are more sensitive than adults. Derivation of application factors with sensitive larvae is less expensive and time-consuming than chronic tests and can be protective of the species.

Oil and Oil Dispersants

Eggs and larvae of aquatic species respond to petroleum oils in experimental systems, but toxicity is related to place of origin of the oil. Acute effects are due to lower boiling aromatics; chronic effects to all fractions, but mainly to those of relatively low volatility. Capuzzo and Lancaster (1981) reviewed effects of oil on crustaceans and reported that 25 ng crude oil/L caused reduction in rate of respiration and oxygen:nitrogen ratios in lobster, Homarus americanus, larvae. Donahue et al. (1977 a) showed that exposure for one hour to 10 per cent fuel oil had no effect on development and survival of larvae of the barnacles, Chthamalus fragilis and Balanus amphitrite niveus. Toxicity to the phototrophic behavior of barnacle nauplii was demonstrated after exposure for one hour to concentrations of petroleum oil between three and 93 per cent of the water-soluble fraction. Used crankcase oil was most toxic and crude oil from Louisiana was least toxic to barnacle phototaxis. Aromatic hydrocarbons, such as benzene, from oils, were not highly toxic.

Katz (1973) added crude oil to artificial seawater, mixed them for 24 hours, and tested the aqueous extract for toxicity to larvae of the crab, Neopanope texana. Larvae maintained in extract from the day of hatch were strongly affected, and the percentage of larvae reaching the megalopa stage

was directly related to age at which exposure began.

Donahue et al. (1977 b) layered one part No. 2 fuel oil over eight parts seawater for 24 hours, drew off the aqueous layer, and tested it for survival of larvae of the stone crab, Menippe mercenaria, spider crab, Libinia dubia, blue crab, C. sapidus, calico crab, Hepatus ephaliticus, fiddler crab, Uca panacea, and striped hermit crab, Clibanarius vittatus. Sensitivity varied greatly among species: blue and fiddler crab zoeae were more resistant than stone crab zoeae. Survival of stone crab zoeae was reduced by four per cent of the water soluble fraction after two days, and all larvae were dead in a 20 per cent solution after three days. The authors concluded that the difference between toxic concentrations of water soluble fractions found in the laboratory and concentrations in seawater seems to be very great, approximately 10^3 or more.

Winters et al. (1977) tested eggs and larvae of C. fragilis, B. amphitrite, C. vittatus, L. dubia, M. mercenaria, and the pteropod, Cresis acicula, against numerous components of the water-soluble fraction of oil. Barnacle eggs and early stages were most susceptible to water-soluble extracts. Most early embryos were killed in 50 per cent mixes. Upon hatching, toxic effects on phototaxis were seen in 25 per cent water-soluble fraction. Larvae of C. vittatus, L. dubia, and M. mercenaria were about equally sensitive to No. 2 fuel oil, 0.6 mg/L (1:25 dilution) inhibiting growth and moulting. With C. acicula, 0.3 mg/L caused death of all exposed animals in three days. Indan, dimethylnaphthalene, diisopropylbenzene, 1-methylnaphthalene, and 1,2,4-trimethylbenzene were the most toxic aromatic compounds in the water-soluble fraction.

Wells (1972) showed that Venezuelan crude oil was toxic to larvae of H. americanus at concentrations as low as 0.001 ml oil/L of seawater. Death

occurred during moulting in 0.002 ml/L, and rate of development was decreased by 0.006 mg/L, in which some larvae did not develop beyond the third stage. Those that did, retained characteristics of earlier stages.

Growth of embryos of the starfish, Patiria miniata, was used to evaluate effects of Santa Barbara (California) oil after exposure for up to 48 hours (Stuermer et al., 1981; Davis et al., 1981). Length of embryos was inversely proportional to hydrocarbon concentration and length of time of exposure. Abnormal morphology was also described. As oil aged within the exposure system, it became less toxic because hydrocarbon concentration decreased with time. The authors concluded that responses to short-term exposure lead to long-term population effects because of toxicity to embryos.

Dispersants are used to break up oil slicks and, presumably, to cause oil to have less effect on organisms. However, dispersants may themselves be toxic and may potentiate effects of oil. Linden (1975) showed that larvae of the Baltic herring were 100 times more sensitive to oil and dispersant than to oil alone. After 96 hours of exposure to the combination, larvae were deformed and the primordial fin destroyed.

Eggs and larvae of the sea urchins, Psammechinus miliaris and Paracentrotus lividus, were treated with Kuwait or Ekofisk oil and a dispersant (Corexit 8666) by Lonning and Hagstrom (1975 a). Concentrations of 1,000 to 20,000 mg of each/L were used. Little effect was found on fertilization and early development, but later embryonic and larval stages were affected. After treatment for only three hours, a dispersant caused inhibition of development of the intestine and loss of organization in the mesenchyme, which led to abnormal skeletal development. When treated with oil and dispersants, oil droplets were found within the cells of the embryos, but the authors did not ascribe effects to the droplets. Lonning and Hagstrom

(1975 a) suggested that dispersants make toxic substances of the water-soluble fraction more available to organisms in the water.

Lonning and Hagstrom (1975 b) also demonstrated effects of eight oil dispersants on fertilization and larval development of the sea urchins, Strongylocentrotus droebachiensis and Strongylocentrotus pallidus, and the fishes, Gadus morrhua and Pleuronectes platessa. Exposure of urchin eggs for three hours to 1,000 mg of dispersants/L caused the mesenchyme to be scattered around the blastocoel, resulting in abnormal skeletal development. Also, differentiation of the gut was abnormal and a cytolytic effect of four dispersants on embryos was described. Fish embryos were more resistant to the dispersants than urchin embryos because the chorion protects them from influences of materials in water. A slight retarding effect was found on cleavage and differentiation, and one dispersant caused cytolysis and death of fish larvae.

Heavy Metals

Freshwater and estuarine systems may be polluted with heavy metals from industrial and municipal sources. Metals of major concern are mercury, cadmium, copper, lead, chromium, zinc, and nickel, although toxicity of other metals has been reported.

In early studies, Wisely and Blick (1967) tested larvae of seven species with mercury, copper, and zinc. The metals caused death of larvae in only two hours, and data were presented as the 2-hour LC50. Mercury was more toxic to all species than copper, and zinc was least toxic. The bryozoans, Watersipora cucullata and Bugula neritina, and the tubeworms, Spirorbis lamellosa and Galeolaria caepitosa, were most sensitive to each metal. Larvae of the bivalves, Mytilis edulus and Crassostrea commercialis, and the brine shrimp, Artemia salina, were relatively insensitive to the three metals. The authors

described precautions to be taken in studies with heavy metals. Addition of copper, for example, reduced pH in experimental vessels, and effects of low pH had to be distinguished from those of the metal ion.

Connor (1972) exposed larvae of the oyster, Crassostrea edulus, and the crustaceans, Crangon crangon, Carcinus maenus, and Homarus gammarus, to mercury, copper, and zinc. As did Wisely and Blick (1967), Connor (1972) reported mercury to be the most toxic metal, as estimated by the ET50. The experiment was conducted for 64 hours, and the logarithm of the concentration and toxicity, as measured by the ET50, was linear for all metals at all times. Larvae were much more sensitive than adults, an observation also noted by Wisley and Blick (1967). Ahsanullah and Arnott (1978) found that larvae of the crab, Paragrapsis quadridentatus, were nine times more sensitive to zinc and 29 times more sensitive to cadmium than adults. Amiard (1976 a) showed that larvae of the crustaceans, C. maenas and Palaemon serratus were much more sensitive to cobalt, strontium, silver, and antimony than adults. Zinc was also shown to be toxic to larvae of the Pacific oyster, Crassostrea gigas, (Brereton et al., 1973). Although adults were unaffected, larval growth was severely inhibited by concentrations of zinc between 100 and 150 µg/L. No growth occurred at 200 µg/L. Boyden et al. (1975) showed that 125 µg zinc/L caused delay in time and numbers of settling of larvae of C. gigas.

Conversely, Pavicic and Jarvenpaa (1974) compared the median tolerance limits of cadmium to larvae and adults of the mussel Mytilis galloprovincialis and found the adult to be more sensitive. The authors pointed out that since the test with adults was conducted for 30 days, and the test with larvae for only two days, the results were not strictly comparable because the larvae may not have had time to accumulate high concentrations of cadmium.

Toxicity of mercury, silver, copper, nickel, and zinc to the larvae of the American oyster, Crassostrea virginica, and the hard clam, Mercenaria mercenaria, were compared by Calabrese et al. (1977). Toxicity was expressed as the concentrations at which 5 per cent (LC5), 50 per cent (LC50), and 95 per cent (LC95) of the larvae died after exposure for eight (clams) and 12 (oyster) days. The two species were equally sensitive to the metals: order of toxicity to oyster larvae was $Hg > Ag > Cu > Ni$; for clam larvae it was $Hg > Cu > Zn > Ni$. Although nickel was the least toxic, it had the greatest effect upon the growth rate of clam larvae. Growth rate at the LC5 concentration was 31.9 per cent that of the control, and no growth occurred at the LC50 concentration. In addition, larvae exposed to nickel were abnormal, with tissues extruded from the shells, Calabrese et al. (1977) concluded that metal concentrations too low to cause direct mortality may prolong pelagic existence of larvae, thus adding to the risk of death by predation, disease, or dispersal.

Nauplii of the freshwater copepods, Cyclops vernalis, Cyclops bicuspidatus, and Diaptomus sp., were exposed to copper, cadmium, lead, mercury, and arsenic by Borgmann (1980) and Borgmann et al. (1980). Their studies differed from most others because natural populations of copepods were used in natural water with a natural food supply. A seasonal cycle of toxicity was found for each metal except arsenic. Growth was the most sensitive response in late fall and winter, and the least sensitive response in early summer. Cadmium, copper, mercury, lead, and zinc reacted synergistically in causing reductions in biomass and productivity of the three species.

Heavy metals can also affect behavior of planktonic larvae. Mirkes et al. (1978) showed that developmental time from the megalopa to the juvenile crab stages of Eurypanopeus depressus was extended by eight days in the presence of 10 μg cadmium/L. Cadmium caused increased mortality at the time of molt from

the megalopa to the crab stage. Mortality among control larvae at molt was 43 per cent, whereas among cadmium-treated larvae, it was 93 per cent. Depressed swimming rate of early zoeal stages was associated with 1.8 μg mercury/L, and increased swimming rate in the late zoeal stages was associated with 10 μg cadmium/L. Amiard (1976 b) showed that the orientation of zoeae of C. maenas and P. serratus to light was affected by high concentrations of cobalt, silver, and strontium.

MacInnes and Calabrese (1979) used response surface methods and factorial analyses to measure effects of temperature, salinity, and copper on development of embryos and 24-hour veliger larvae of C. virginica. Salinity had a greater effect than temperature on embryos at 0, 5, and 10 μg copper/L, but they had equal effect at 20 μg copper/L. Ability of embryos to adapt to temperature and salinity was impaired by 20 μg copper/L. The authors concluded that low concentrations of copper may strongly suppress recruitment of oyster embryos during periods of persistently low salinity and high or low temperature. For methods of testing C. virginica and other bivalves, see ASTM (1980).

Alderdice et al. (1979 a, b, c) demonstrated that cadmium affected several vital processes in eggs of Pacific herring, Clupea harengus, at salinities of 5, 20, and 35 parts per thousand. Both absolute concentration of cadmium in the water, and ratio of cadmium to calcium as related to salinity, affected the jelly coat and capsule of eggs, making them susceptible to mechanical damage. This was particularly true at concentrations of 1 mg cadmium/L and above and salinities of 20 parts per thousand and below. The volume of fertilized eggs was reduced after exposure to as little as 0.1 mg/L, and 1 mg/L caused reduction in osmolality of perivitelline fluid after 48 hours of exposure. Significantly contaminated eggs did not recover when transferred to clean seawater, probably because cadmium was bound strongly to the capsule and jelly coat.

Copper is much more toxic to fish eggs than cadmium. Steele et al. (1973) demonstrated low survival of herring eggs after exposure to 10 μg copper/L, and Blaxter (1977) reported death of plaice and herring embryos exposed to 30 μg /L of copper. Rice and Harrison (1978) studied effects of copper on cumulative mortality, percentage hatching, and larval length upon hatching of C. harengus eggs. Significant mortality of embryos occurred at 35 μg /L; significant mortality of larvae, 0.3 μg /L. Larvae hatched from exposed eggs grew significantly less than those exposed during later developmental stages. Westernhagen et al. (1979) exposed herring eggs to mixtures of copper, cadmium, and lead. Viable hatch was inhibited significantly when all three metals were present in water. Lead inhibited uptake of copper but promoted uptake of cadmium, demonstrating that uptake and toxicity of a metal is affected by the presence of other metals. See Kaiser (1980) for a discussion of factors that affect chemical actions of metals in water.

Pesticides

A large number of studies have been done on effects of pesticides, particularly insecticides, on meroplankton. A large portion of the meroplankton is composed of larval arthropods, and it is to be expected that they would be affected by insecticides.

Chlorinated hydrocarbon insecticides, used extensively in the past and still used in some parts of the world, are toxic to marine larvae. Newer formulations, such as organophosphates, carbamates, pyrethroids, and juvenile hormone mimics, are less persistent than chlorinated hydrocarbons, but may be highly toxic to crustaceans.

Effects of pesticides on larval crustaceans include death, retardation of moulting and metamorphosis, and behavioral changes. Armstrong et al. (1976) showed that acute and chronic toxicity of the chlorinated hydrocarbon

insecticide, methoxychlor, to the dungeness crab, Cancer magister, was inversely related to age after hatching and directly related to length of time of exposure. The 96-hour LC50's for zoea, juveniles, and adults were 0.4, 5.1 and 130 $\mu\text{g/L}$, respectively, but 0.05, 0.4, and 4.0 $\mu\text{g/L}$ decreased survival during exposures of more than 60 days. Although methoxychlor did not affect hatching at concentrations up to 10 $\mu\text{g/L}$, moulting of prezoeae to zoeae was 30 per cent less than the controls. Methoxychlor concentrations between 0.05 and 4.0 $\mu\text{g/L}$ delayed moulting of larval and juvenile crabs for up to 10 days. Similar results with C. magister and the carbamate insecticide, carbaryl, were reported by Buchanan et al. (1970), who showed that 1 mg/L did not affect egg hatching, but prevented moulting of all prezoeae to zoeae. The 96-hour LC50 for the first zoeal stage was 10 $\mu\text{g/L}$. Moulting was delayed by 0.1 μg carbaryl/L. Epifanio (1971) showed the larvae of the crabs, Leptodius floridanus and Panopeus herbstii, were unable to complete development in 10 $\mu\text{g/L}$ of dieldrin, a chlorinated hydrocarbon insecticide. Highest mortality was during the zoeal stage. Conversely, captan, a fungicide, did not affect survival of C. magister zoeae exposed to 30 $\mu\text{g/L}$ for 69 days (Caldwell et al., 1978).

As with heavy metals, most larvae of meroplanktonic species are more sensitive to pesticides than are adults. Dijk et al. (1977) compared responses of first instar larvae and adults of three species of shrimp, Palaemon elegans, C. crangon, and Palaemonetes varians, to sodium pentachlorophenate. The 96-hour LC50 concentrations, in mg/L, were: C. crangon, first instar, 0.1 adult, 1.8; P. elegans, first instar, 0.08; adult, 10.4; P. varians, first instar, 0.4; adult, 5.1. In a series of four reports, Bookhout and his coworkers demonstrated a variety of effects of pesticides on larvae of the crabs, Callinectes sapidus and Rhithropanopeus harrisii, (Bookhout et al.,

1971, 1976, 1980; Bookhout and Costlow, 1975; Bookhout and Monroe, 1977). The chlorinated insecticide, mirex, extended the duration of developmental stages of R. harrisii at 0.01 µg/L, but had no effect on duration of development from hatching to the first crab stage in C. sapidus at up to 0.1 µg/L. However, 1.0 µg mirex/L was acutely toxic to C. sapidus larvae, with only two per cent of exposed larvae reaching the megalopa stage. Conversely, larvae of C. sapidus were much more sensitive to methoxychlor than were larvae of R. harrisii. Larvae of R. harrisii were most susceptible to methoxychlor at the first stage of development, whereas C. sapidus larvae were most susceptible in the later stages.

The juvenile hormone mimic, methoprene, reduced survival of zoeal larvae of R. harrisii at concentrations as low as 10 µg/L, and no larvae survived beyond the first zoeal stage when exposed to 1 mg/L. The first zoeal stage was the most sensitive of the larval stages (Christiansen et al., 1977). Forward and Costlow (1978) reported that sublethal concentrations of methoprene had no effect on swimming rates or phototaxis of the larvae of R. harrisii. Another insect growth regulator, hydroprene, caused significant increase in swimming speed of stage IV zoeae exposed to 0.05 and 0.1 mg/L. A third insect growth regulator, diflubenzuron, was lethal to first zoeal larvae of R. harrisii at 10 µg/L (Christiansen et al., 1978) and caused significant increases in swimming speeds of stages I, II, and III zoeae at 0.3 µg/L (Forward and Costlow, 1978). Phototaxis of stage IV zoeae was altered by 0.1 µg diflubenzuron/L. Christiansen and Costlow (1982) showed that 10 µg diflubenzuron/L caused deformation of the endocuticle and exocuticle, indicating that chitin synthesis was inhibited.

In most toxicity test, animals are exposed continuously for a specific length of time or for a time related to developmental stages. Armstrong and

Milleman (1974), however, exposed fertilized eggs and six developmental stages of the bay mussel, Mytilis edulus, to several concentrations of carbaryl for only one hour, after which, they were transferred to clean seawater.

Forty-eight hours after fertilization, the number of normal and abnormal larvae were counted and 1-hour EC50 values were calculated for abnormality. The most sensitive developmental stage was that of the first polar body, which occurred approximately 20 minutes after fertilization. Its 1-hour EC50 was 5.3 mg/L. Sensitivity decreased with each stage thereafter to the early veliger stage, 32 hours after fertilization, when the EC50 was 24.0 mg/L. The authors presented evidence that exposure of early developmental stages to carbaryl and its degradation products results in a significant rise in DNA content and that there is severe interference with synthesis of protein and DNA-dependent RNA. They also noted that carbaryl and its derivatives are known to poison mitotic spindles, and since unalignment of cleavage occurred, this could have caused abnormalities in early stages.

Although crustaceans are particularly sensitive to pesticides, embryos and larvae of other groups of animals may be affected by them. Hooftman and Vink (1980) exposed 2- to 3-day old larvae of the polychaete, Ophryotrocha diadema, to pesticides. In 96-hour tests, the LC50's for pentachlorophenol were 0.6 mg/L for larvae and 1.2 mg/L for adults; for 3,4-dichloroaniline they were 4 mg/L for larvae and 15 mg/L for adults, but the LC50 for dieldrin was less than 0.1 mg/L for both larvae and adults. In long-term studies, individuals exposed to 0.34 mg dieldrin/L as larvae did not reproduce as adults.

Sea urchin eggs and embryos have been used extensively in toxicity testing. Bresch and Arendt (1977) stated that sea urchins, Sphaerechinus granularis and Paracentrotus lividus, could be used as models for observations of effects of toxicants on cleavage and differentiation. Dieldrin had no

effect, but heptachlor, DDT, and methoxychlor caused abnormal development and lysis of embryos.

Brooks (1981) reviewed literature on effects of pesticides on anuran development and exposed eggs and larvae of the frog, Limnodynastes tasmaniensis, to dieldrin. Tadpoles exposed to 0.1 mg dieldrin/L during neuralization exhibited abnormalities of the otolith, otic capsule, and cephalic pigmentation.

Industrial and Municipal Effluents

Effects of vinyl chloride production waste on behavior of barnacle, Balanus balanoides, larvae and juveniles were described by Rosenberg (1972). The waste contained mainly 1,2-dichloroethane and 1,1,2-trichloroethane, as well as approximately 20 other chlorinated aliphatic hydrocarbons. After 96 hours of exposure, 2 mg of waste/L reduced the swimming activity of stage II nauplii, and 4 mg/L reduced the swimming activity of stages V and VI nauplii. Few stage VI nauplii moulted to cypris larvae in concentrations above 2 mg/L. In juveniles, cirri beat normally in concentrations below 10 mg/L for 120 hours, and most animals were active for the same period of time at 25 mg/L. At 100 mg/L, however, only 20 per cent of the juveniles survived after 120 hours. Newly settled, 2 to 3 week old specimens were about 10 times more tolerant than stage II nauplii.

Chlorine occurs in many waste waters, and when it reaches seawater, reacts to form chloramine. Effects of chloramine and chlorine on larval stages of H. americanus were reported by Capuzzo et al. (1976) and Capuzzo (1977). In continuous-flow tests, chloramine was more toxic than free chlorine to stage I larvae: the 48-hour LC50 for free chlorine was 16.3 mg/L, whereas it was 2.0 mg/L for chloramine. Nineteen days after exposure for only one hour to 1.0 mg chlorine or chloramine/L, dry weight and respiration rate were significantly

lower than in unexposed larvae. The authors concluded that acute exposure to chlorine or chloramine reduced growth and metabolic activity of the larval lobsters, noting that interference with metabolic processes could result in inefficient utilization of food with subsequent reduction of growth.

Another halogen compound, bromate (BrO_3^-) is a stable end-product of exposure of seawater to sunlight. Richardson *et al.* (1981) showed that newly-hatched larvae of the striped bass, *Morone saxatilis*, were more sensitive to bromate than four-day old larvae (however 2-day LC_{50} = 605 mg/L; 10-day LC_{50} = 92.6 mg/L). Eggs were less sensitive: 500 mg bromate/L caused 42 per cent reduction in hatch.

Naphthalene is a common constituent of municipal wastes. Sanborn and Malins (1977) reported that 8 $\mu\text{g/L}$ caused 100 per cent mortality of newly hatched *C. magister* zoeae and of stages I and V of the spot shrimp, *Pandalus platyceros*. Shrimp larvae contained 820 g/Kg, approximately 100 times the exposure concentration, but all naphthalene was depurated within 36 hours after the shrimp were placed in clean water. However, metabolic products of naphthalene constituted 21 per cent of the original body burden and were strongly resistant to depuration.

Kinae *et al.* (1981) tested ether extracts of the effluent from a Kraft pulp mill for effects on survival of sea urchin, *Anthocidaris crassispina*, eggs. Neutral, acidic, basic, amphoteric, and phenolic subfractions affected fertilization, blastulation, and gastrulation, but the basic fraction was most toxic. The lowest concentration of any subfraction that affected development was 1 mg/L.

Frog embryos and larvae were used by Greenhouse (1976) to demonstrate toxicity of hydrazine, methylhydrazine, dimethyl hydrazine, and N-phenyl- α -naphthylamine. Embryos were more resistant than larvae in the leopard frog,

Rana pipiens, and the South African clawed toad, Xenopus laevis. Greenhouse reviewed the relatively small literature on use of anurans in biological tests and concluded that X. laevis is an excellent organism for use in toxicity and teratogenicity tests.

EFFECTS OF POLLUTANTS ON SETTLING OF MEROPLANKTON

Settling of meroplankton may be affected by pollutants in the water column (Tagatz et al., 1977). Mileikovsky (1970) pointed out that concentrations of pollutants may be much higher in the substratum than in the water column and stated that pelagic larvae of benthic invertebrates die quickly after settling on contaminated substrata. See Pearson and Rosenberg (1978) for a discussion of this subject.

Tagatz and his coworkers have published a series of papers that demonstrate effects of pollutants on communities that originate from meroplankton. In their laboratory tests, natural seawater with its constituent plankton flowed over clean sand. Some portions of the water were treated with pollutants and others were untreated controls. The test is described in detail by Tagatz et al. (1977) and Hansen and Tagatz (1980). The pesticides, pentachlorophenol (Tagatz et al., 1977, 1978 b, 1981), carbaryl (Tagatz et al., 1979 a), and fenvalerate (Tagatz and Ivey, 1981), had strong effects on colonization by larval annelids, arthropods, echinoderms, molluscs, and nemerteans. Mollusk larvae were most sensitive to the pesticides. Their numbers were significantly lower in treated samples, and growth of the clam, Ensis minor, was strongly affected by 11 μg carbaryl/L. The amphipod, Corophium acherusicum, was particularly sensitive to carbaryl. Its numbers were significantly decreased by 1.1 μg /L and it was absent from the community at 11.1 μg /L.

Meroplanktonic communities affected by pollutants before settling may be

more sensitive than the benthic communities that develop from them. Tagatz and Deans (in press) described a method by which structure of laboratory-developed communities could be compared with structure of field-developed communities. When treated with the insecticide, chlorpyrifos, molluscan larvae were sensitive to approximately 0.1 $\mu\text{g/L}$, but the later developmental stages that characterize the field-developed community were not sensitive to 5.9 $\mu\text{g/L}$.

In another type of test, various muds used in oil drilling operations were incorporated into sand and the communities that developed were analyzed (Tagatz and Tobia, 1978; Tagatz *et al.*, 1978 a, 1979 b, 1982; Cantelmo *et al.*, 1979). Barite (BaSO_4) caused significant reductions in numbers of species and individuals at one part barite and either 3 or 10 parts sand. Settling by annelid larvae was particularly affected. Mollusk larvae were affected when sand was covered by barite. Lignosulfonate type muds, when suspended in the water column, caused significant structural changes in settling communities.

In a similar type of experiment, Borthwell and Stockner (1980) reported that secondarily treated Kraft mill waste caused inhibition of accumulation of attached algal biomass after five days of exposure in Plexiglas troughs on the bank of a river. After that time, new species settled in the troughs and biomass increased sharply.

Studies of the above types are important for consideration of short-term effects after local contamination from dredge and fill or oil drilling operations and for consideration of long-term effects when sediment acts as a sink for pollutants. The experiments indicate whether organisms can survive in the sediments and if recruitment can occur from the meroplankton after contamination.

REFERENCES

- Ahsanullah, M. and G.H. Arnott (1978) Acute toxicity of copper, cadmium, and zinc to larvae of the crab Paragrapsis quadridentatus (H. Milne Edwards) and implications for water quality criteria. Australian Journal of Marine and Freshwater Research 29, 1-8.
- AIBS (1978) The Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills. American Institute of Biological Sciences. Washington, D.C. 935 pp.
- Alderdice, D.F., T.R. Rao, and H. Rosenthal (1979a) Osmotic responses of eggs and larvae of the Pacific herring to salinity and cadmium. Helgolander Wissenschaftliche Meeresuntersuchungen 32, 508-538.
- Alderdice, D.F., H. Rosenthal, and F.P.J. Velsen (1979b) Influence of salinity and cadmium on the volume of Pacific herring eggs. Helgolander Wissenschaftliche Meeresuntersuchungen 32, 163-178.
- Alderdice, D.F., H. Rosenthal, and F.P.J. Velsen (1979c) Influence of salinity and cadmium on capsule strength in Pacific herring eggs. Helgolander Wissenschaftliche Meeresuntersuchungen 32, 149-162.
- Amiard, J.C. (1976a) Etude experimentale de la toxicite argue de sels de cobalt, d'antimoine, de strontium et d'argent chez quelques crustaces et leurs larves et chez quelques teleosteens. Revue Internationale d'Oceanographie Medicale 43, 79-95.
- Amiard, J.C. (1976b) Les variations de la phototaxie des larves de crustaces sous l'action de divers polluants metalliques; mise au point d'un test de toxicite sublethale. Marine Biology 34, 239-245.

- Amiard, J.C., and C. Amiard-Triquet (1975) Experience preliminaire a l'utilisation d'une chaines trophique marine dans l'etude d'une pollution par le cobalt 60: bilan apres une ingestion unique. Water, Air, and Soil Pollution 5, 221-229.
- Amiard-Triquet, C. (1979) Modalites de la contamination du deux chaines trophique dulcaquicoles par le cobalt 60. Water, Air, and Soil Pollution 12, 155-170.
- Anderson, J.W., J.M. Neff, B.A. Cox, H.E. Tatum, and G.M. Hightower (1974) Characteristics of dispersions and water soluble extracts of crude and refined oils and their toxicity to estuarine crustaceans and fish. Marine Biology 27, 75-88.
- Apperson, C.S., C.H. Schaeffer, A.S. Colwell, G.H. Wermer, N.L. Anderson, E.F. Dupras, Jr., and D.R. Loganecker (1978) Effects of diflubenzuron on Chaeoborus astictopus and nontarget organisms and persistence of diflubenzuron in benthic habitats. Journal of Economic Entomology 71, 521-527.
- Armstrong, D.A., D.V. Buchanan, M.H. Mallon, R.S. Caldwell, and R.E. Milleman (1976) Toxicity of the insecticide methoxychlor to the Dungeness crab Cancer magister. Marine Biology 38, 239-254.
- Armstrong, D.A. and R.A. Milleman (1974) Effects of the insecticide Sevin and its first hydrolytic product, 1-naphthol, on some early developmental stages of the bay mussel Mytilus edulus. Marine Biology 28, 11-15.
- Arnott, G.H. and M. Ahsanullah (1979) Acute toxicity of copper, cadmium and zinc to three species of marine copepod. Australian Journal of Marine and Freshwater Research 30, 63-71.

- ASTM (1980) Standard practice for conducting static acute toxicity tests with larvae of four species of bivalve molluscs. pp. 1-17, in Annual Book of ASTM Standards, American Society for Testing and Materials. Philadelphia
- Baeyens, W., G. Decadt, and I. Elskens (1979) A study of the distribution of mercury in the various compartments of the North Sea and Scheldt Estuary ecosystems. Oceanologica Acta 2, 447-457.
- Batterton, J.C., K. Winters, and C. van Baalen (1978) Sensitivity of three microalgae to crude oils and fuel oils. Marine Environmental Research 1, 31-44.
- Bentley-Mowat, J.A. and S.M. Reid (1977) Survival of marine phytoplankton in high concentrations of heavy metals, and uptake of copper. Journal of Experimental Marine Biology and Ecology 26, 249-264.
- Bertrum, P.E. and B.A. Hart (1979) Longevity and reproduction of Daphnia pulex (de Geer) exposed to cadmium contaminated food or water. Environmental Pollution 16, 295-305.
- Biesinger, K.E. and G.M. Christensen (1972) Effects of various metals on survival, growth, reproduction, and metabolism of Daphnia magna. Journal of the Fisheries Research Board of Canada 29, 1691-1700.
- Biggs, D.C., R.G. Rowland, H.B. O'Connors, Jr., C.D. Powers, and C.F. Wurster (1978) A comparison of the effects of chlordane and PCB on the growth, photosynthesis, and cell size of estuarine phytoplankton. Environmental Pollution 15, 253-263.
- Birge, W.J., J.A. Black, and A.G. Westerman (1979) Evaluation of aquatic pollutants using fish and amphibian eggs as bioassay organisms. pp. 108-118, in Animals as Monitors of Environmental Pollutants. National Academy of Sciences, Washington, D.C.

- Birge, W.J., A.G. Westerman, and O.W. Roberts (1974) Lethal and teratogenic effects of metallic pollutants on vertebrate embryos. pp. 316-320, in Second Annual NSF-RANN Trace Contaminants Conference, Asilomar, California, National Technical Information Service, Springfield, Virginia.
- Blaxter, J.H.S. (1977) The effect of copper on the eggs and larvae of plaice and herring. Journal of the Marine Biological Association of the United Kingdom 57, 849-858.
- Bookhout, C.G., and J.D. Costlow, Jr. (1975) Effects of mirex on the larval development of the blue crab. Water, Air, and Soil Pollution 4, 113-126.
- Bookhout, C.G., J.D. Costlow, Jr., and R. Monroe (1976) Effects of methoxychlor on larval development of mud-crabs and blue crab. Water, Air, and Soil Pollution 5, 349-365.
- Bookhout, C.G., J.D. Costlow, Jr., and R. Monroe (1980) Kepone effects on larval development of mud-crabs and blue crabs. Water, Air, and Soil Pollution 13, 57-77.
- Bookhout, C.G., and R.J. Monroe (1977) Effects of malathion on the development of crabs. pp. 3-9, in Physiological Responses of Marine Biota to Pollutants, F.J. Vernberg, A. Calabrese, F.P. Thurnberg, and W.V. Vernberg, eds., Academic Press, New York.
- Bookhout, C.G., A.J. Wilson, Jr., T.W. Duke, and J.I. Lowe (1971) Effects of mirex on the larval development of two crabs. Water, Air, and Soil Pollution 1, 165-180.
- Borgmann, U., R. Cove, and C. Loveridge (1980) Effects of metals on the biomass production kinetics of freshwater copepods. Canadian Journal of Fisheries and Aquatic Sciences 37, 567-575.

- Borgmann, U. (1980) Interactive effects of metals in mixtures on biomass production kinetics of freshwater copepods. Canadian Journal of Fisheries and Aquatic Sciences 37, 1275-1302.
- Bothwell, M.L., and J.G. Stockner (1980) Influence of secondarily treated Kraft mill effluent on the accumulation rate of attached algae in experimental continuous-flow troughs. Canadian Journal of Fisheries and Aquatic Science 37, 248-254.
- Boudou, A., and F. Ribeyre (1981) Comparative study of the trophic transfer of two mercury compounds - HgCl_2 and CH_3HgCl_3 - between Chlorella vulgaris and Daphnia magna. Influence of temperature. Bulletin of Environmental Contamination and Toxicology 27, 624-629.
- Boyden, C.R., H. Watling, and I. Thornton (1975) Effect of zinc on the settlement of oysters Crassostrea gigas. Marine Biology 31, 227-234.
- Boylan, D.B., and B.W. Tripp (1971) Determination of hydrocarbons in seawater extracts of crude oil and crude oil fractions. Nature 230, 44-47.
- Braek, G.S., D. Malnes, and A. Jensen (1980) Heavy metal tolerance of marine phytoplankton. IV. Combine effect of zinc and cadmium on growth and uptake in some marine diatoms. Journal of Experimental Marine Biology and Ecology 42, 39-54.
- Brereton, A., H. Lord, I. Thornton, and J.S. Webb (1973) Effects of zinc on growth and development of larvae of the Pacific oyster Crassostrea gigas. Marine Biology 19, 96-101.
- Bresch, H. and U. Arendt (1977) Influences of different organochlorine pesticides on the development of the sea urchin embryo. Environmental Research 13, 121-128.

- Brooks, J.A. (1981) Otolith abnormalities in Limnodynastes tasmaniensis tadpoles after embryonic exposure to the pesticide dieldrin. Environmental Pollution (Series A) 25, 19-25.
- Brown, B., and M. Ahsanullah (1971) Effects of heavy metals on mortality and growth. Marine Pollution Bulletin 2, 182-187.
- Buchanan, D.V., R.E. Milleman, and N.E. Stewart (1970) Effects of the insecticide Sevin on various stages of the Dungeness crab, Cancer magister. Journal of the Fisheries Research Board of Canada 27, 93-104.
- Buikima, A.L., Jr., B.R. Niederlehner, and J. Cairns, Jr. (1981) The effects of a simulated refinery effluent and its components on the estuarine crustacean, Mysidopsis bahia. Archives of Environmental Contamination and Toxicology 10, 231-240.
- Calabrese, A., J.R. MacInnes, D.A. Nelson, and J.E. Miller (1977) Survival and growth of bivalve larvae under heavy metal stress. Marine Biology 41, 179-184.
- Caldwell, R.S., D.A. Armstrong, D.V. Buchanan, M.H. Mallon, and R.E. Milleman (1978) Toxicity of the fungicide captan to the Dungeness crab, Cancer magister. Marine Biology 48, 11-17.
- Cantelmo, F.R., M.E. Tagatz, and K.R. Rao (1979) Effect of barite on meiofauna in a flow-through experimental system. Marine Environmental Research 2, 301-309.
- Capuzzo, J.M., S.A. Lawrence, and J.A. Davidson (1976) Combined toxicity of free chlorine, chloramine, and temperature to stage I larvae of the American lobster, Homarus americanus. Water Research 10, 1093-1099.
- Capuzzo, J.M. (1977) The effect of free chlorine and chloramine on growth and respiration rates of the larval lobster Homarus americanus. Water Research 11, 1021-1024.

- Capuzzo, J.M. (1979) The effects of halogen toxicants on survival, feeding, and egg production of the rotifer, Brachionus plicatilis. Estuarine and Coastal Marine Science 8, 307-316.
- Capuzzo, J.M., and B.A. Lancaster (1981) Physiological effects of South Louisiana crude oil on larvae of the American lobster Homarus americanus. pp. 405-423, in Biological Monitory of Marine Pollutants, J. Vernberg, A. Calabrese, F.P. Thurberg, and W.B. Vernberg, eds., Academic Press, New York.
- Chan, K., K.H. Wong, and S.L. Ng (1981) Effects of polyethylene glycol on growth and cadmium accumulation of Chlorella salina. Chemosphere 10, 981-991.
- Christiansen, M.E., and J.D. Costlow, Jr (1982) Ultrastructural study of the exoskeleton of an estuarine crab Rithropanopius harrisii: effect of the insect growth regulator Dimilin (diflubenzuron) on the formation of the larval cuticle. Marine Biology 66, 217-226.
- Christiansen, M.E., J.D. Costlow, Jr., and R.T. Monroe (1977) Effects of the juvenile hormone mimic ZR-515 (Altosid) on larval development of the mud-crab Rithropanopius harrisii in various salinities and cyclic temperatures. Marine Biology 39, 209-279.
- Christiansen, M.E., J.D. Costlow, Jr., and R.T. Monroe (1978) Effects of the insect growth regulator Dimilin (TH6040) on larval development of two estuarine crabs. Marine Biology 50, 29-36.
- Conner, P.M. (1972) Acute toxicology of heavy metals to some marine larvae. Marine Pollution Bulletin 3, 190-192.
- Conover, R.J. (1971) Some relations between zooplankton and bunker C oil in Chedabucto Bay following the wreck of the tanker Arrow. Journal of the Fisheries Research Board of Canada 28, 1327-1330.

- Corner, E.D.S. (1978) Pollution studies with Marine Plankton. Part I. Petroleum hydrocarbons and related compounds. Advances in Marine Biology 15, 289-380.
- Cunningham, P.A., and D.S. Grosch (1978) A comparative study of the effects of mercuric chloride and methyl mercuric chloride on reproductive performance in the brine shrimp Artemia salina. Environmental Pollution 15, 83-99.
- Davies, A.G. (1973) The kinetics of a preliminary model for the uptake of radio-zinc by Phaeodactylum tricornutum in culture. Radioactive Contamination on the Marine Environment, pp. 403-420, IAEA, Vienna.
- Davies, A.G. (1978) Pollution studies with marine plankton Part II. Heavy metals. Advances in Marine Biology 15, 381-508.
- Davis, P.H., T.W. Schultz, and R. B. Spies (1981) Toxicity of Santa Barbara seep oil to starfish embryos: Part 2-The growth bioassay. Marine Environmental Research 5, 287-294.
- Dawson, J.K. (1979) Copepods (Arthropoda: Crustacea: Copepoda) pp. 145-170, in Pollution Ecology of Estuarine Invertebrates, C.W. Hart, Jr. and S.L.H. Fuller, eds., Academic Press, New York.
- Dijk, J.J. van, C. van der Meer, and M. Wijnans (1977) The toxicity of sodium pentachlorophenolate for three species of decapod crustaceans and their larvae. Bulletin of Environmental Contamination and Toxicology 17, 622-630.
- Dobroski, C.J., Jr. and C.E. Epifanio (1980) Accumulation of benzo(a)pyrene in a larval bivalve via trophic transfer. Canadian Journal of fisheries and Aquatic Sciences 37, 2318-2322.
- Donahue, W.H., R.T. Wang, M. Welch, and J.A.C. Nicol (1977a) Effects of water soluble components of petroleum oils and aromatic hydrocarbons on barnacle larvae. Environmental Pollution 13, 188-202.

- Donhue, W.H., M.F. Welsh, W.Y. Lee, and J.A.C. Nicol (1977b) Toxicity of water soluble fractions of petroleum oils on larvae of crabs. pp. 77-94, in Pollution Effects on Marine Organisms, C.S. Gram, ed., Lexington Books, Lexington, Massachusetts.
- Dunstan, W.M., L.P. Atkinson, and J. Natoli (1975) Stimulation and inhibition of phytoplankton growth by low molecular weight hydrocarbons Marine Biology 31, 305-310.
- Eaton, J.G. (1973) Recent developments on the use of laboratory bioassays to determine "safe" levels of toxicants for fish. pp. 107-115, Bioassay Techniques and Environmental Chemistry, G.E. Glass, ed., Ann Arbor Science Publishers, Ann Arbor, Michigan.
- Eide, I., A. Jensen and S. Melsom (1979) Application of in situ cage culture of phytoplankton for monitoring heavy metal pollution in two Norwegian fjords. Journal of Experimental Marine Biology and Ecology 37, 271-286.
- Epifanio, C.E. (1971) Effects of dieldrin in seawater on the development of two species of crab larvae, Leptodius floridanus and Panopeus herbstii. Marine Biology 11, 356-362.
- Fezy, J.S., D.F. Spencer, and R.W. Greene (1979) The effects of nickel on the growth of the freshwater diatom Navicula pelliculosa. Environmental Pollution 20, 131-137.
- Fisher, N.S. (1977) On the differential sensitivity of estuarine and open-ocean diatoms to exotic chemical stress. American Naturalist 111, 871-876.
- Fisher, N.S., E.J. Carpenter, C.C. Remsen, and C.F. Wurster (1974) Effects of PCB on interspecific competition in natural and gnotobiotic phytoplankton communities in continuous and batch cultures. Microbial Ecology 1, 39-50.

- Fisher, N.S., and G.J. Jones (1981a) Effects of copper and zinc on growth, morphology, and metabolism of Asterionella japonica (Cleve). Journal of Experimental Marine Biology and Ecology 51, 37-56.
- Fisher, N.S., and G.J. Jones (1981b) Heavy metals and marine phytoplankton: correlation of toxicity and sulfhydryl binding. Journal of Phycology 17, 108-111.
- Forrester, W.D. (1971) Distribution of suspended oil particles following the grounding of the tanker Arrow. Journal of Marine Research 29, 151-170.
- Forward, R.B., Jr. and J. D. Costlow, Jr. (1978) Sublethal effects of insect growth regulators upon crab larvae behavior. Water, Air, and Soil Pollution 9, 227-238.
- Fujita, M., K. Iwasaka, and E. Takabatake (1977) Intracellular distribution of mercury in freshwater diatom, Synedra cells. Environmental Research 14, 1-13.
- Gachter, R., and W. Geiger (1979) Melimex, an experimental heavy metal pollution study: behaviour of heavy metals in an aquatic food chain. Schweizerische Zeitschrift fur Hydrologie 41, 277-290.
- Gaur, J.P., and H.D. Kumar (1981) Growth response of four microalgae to three crude oils and a furnace oil. Environmental Pollution (Series A) 25, 77-85.
- Gipps, J.F., and B.A.W. Collier (1980) Effect of physical and culture conditions on uptake of cadmium by Chlorella pyrenoidosa. Australian Journal of Marine and Freshwater Research 31, 747-755.
- Glover, R.S., G.A. Robinson, and J.M. Colebrook (1970) Plankton in the North Atlantic - an example of the problems of analyzing variability in the environment. F.A.O. Technical Conference on Marine Pollution. F.A.O. Rome.

- Gordon, D.C., Jr., and N.J. Prouse (1973) The effects of three oils on marine phytoplankton photosynthesis. Marine Biology 22, 329-333.
- Greenhouse, G. (1976) The evaluation of toxic effects of chemical in fresh water by using frog embryos and larvae. Environmental Pollution 11, 303-315.
- Grice, G.D. and M.R. Reeve (eds.) (1982) Marine Mesocosms: Biological and Chemical Research in Experimental Ecosystems. Springer-Verlag, New York.
- Griffiths, P.R.E. (1980) Morphological and ultrastructural effects of sublethal cadmium poisoning on Daphnia. Environmental Research 22, 277-284.
- Guillard, R.R.L. and J.H. Ryther (1962) Studies of marine planktonic diatoms. I Cyclotella nana Hustedt and Detonula confervacea (Cleve) Gran. Canadian Journal of Microbiology 8, 229-239.
- Hansen, D.J. and M.E. Tagatz (1980) A laboratory test for assessing impacts of substances on developing communities of benthic estuarine organisms. pp. 40-57, in Aquatic Toxicology, Proceedings of the Third Annual Symposium on Aquatic Toxicology. P.R. Parrish, J.G. Eaton, and A.C. Hendricks, eds. American Society for Testing and Materials, Special Technical Publication 707, Philadelphia, PA.
- Harding, G.C.H. and W.P. Vass (1979) Uptake from seawater and clearance of p,p -DDT by marine planktonic crustacea. Journal of the Fisheries Research Board of Canada 36, 247-254.
- Harding, G.C.H., W.C. Vass, and K.F. Drinkwater (1981) Importance of feeding, direct uptake from seawater and transfer from generation to generation in the accumulation of an organochlorine (p,p -DDT) by the marine plankton copepod, Calanus finmarchicus. Canadian Journal of Fisheries and Aquatic Sciences 38, 101-119.

- Hart, B.A. and B.D. Scaife (1977) Toxicity and bioaccumulation of cadmium in Chlorella pyrenoidosa. Environmental Research 14, 401-413.
- Hart, B.A., P.E. Bertrum, and B.D. Scaife (1979) Cadmium transfer by Chlorella pyrenoidosa. Environmental Research 18, 327-335.
- Hatakeyama, S. and M. Yasuno (1981a) The effects of cadmium - accumulated Chlorella on the reproduction of Moina macrocopa (Cladocera). Ecotoxicology and Environmental Safety 5, 341-350.
- Hatakeyama, S. and H. Yasuno (1981b) Effects of cadmium on the periodicity of parturition and brood size of Moina macrocopa, (Cladocera) Environmental Pollution (Series A) 26, 111-120.
- Herbes, S.E and G.F. Risi (1978) Metabolic alteration and excretion of anthracene by Daphnia pulex. Bulletin of Environmental Contamination and Toxicology 18, 147-155.
- Hessler, A. (1974) The effects of lead on algae. I. Effects of Pb on viability and mortality of Platymonas subcordiformis (Chlorophyta, Volvocales). Water, Air, and Soil Pollution 3, 371-385.
- Hooftman, R.N. and G.J. Vink (1980) The determination of the effects of pollutants with the marine polychaeta worm Ophryotrocha diadema. Ecotoxicity and Environmental Safety 4, 252-262.
- Hsiao, S.I.C. (1978) Effects of crude oils on the growth of arctic marine phytoplankton. Environmental Pollution 17, 93-107.
- Huisman, J., H.G.J. Ten Hooper, and A. Fuchs (1980) The effects of temperature upon the toxicity of mercuric chloride to Scenedesmus acutus. Environmental Pollution (Series A) 22, 133-148.
- Ignathiades, L. and N. Mimicos (1977) Ecological responses of phytoplankton on chronic oil pollution. Environmental Pollution 13, 109-118.

- Isensee, A.R. and R.S. Yoakum (1980) Freshwater micro-ecosystem development and testing of substitute chemicals. Ecological Research Series, EPA - 60013-80-008, U.S. Environmental Protection Agency, Washington, D.C. 36 pp.
- Jennings, J.R. and P.S. Rainbow (1979) Accumulation of cadmium by Dunaliella tertiolecta. Journal of Plankton Research 1, 67-74.
- Kaiser, K.L.E. (1980) Correlation and prediction of metal toxicity to aquatic biota. Canadian Journal of Fisheries and Aquatic Sciences 37, 211-218.
- Katz, L.M. (1973) The effects of water soluble fractions of crude oil on larvae of the decapod crustacean Neopanope texana (Say). Environmental Pollution 5, 199-204.
- Kauss, P.B. and T.C. Hutchinson (1975) The effects of water soluble petroleum components on the growth of Chlorella vulgaris. Environmental Pollution 9, 157-174.
- Kahn, H.M. and M.A.Q. Khan (1974) Biological magnification of photodieldrin by food chain organisms. Archives of Environmental Contamination and Toxicology 2, 289-301.
- Kinae, N., T. Hashizume, T. Makita, I. Tomita, and I. Kimura (1981) Kraft pulp mill effluents and sediment can retard development and lyse sea urchin eggs. Bulletin of Environmental Contamination and Toxicology 27, 616-623.
- Klotz, R.L. (1981) Algal response to copper under riverine conditions. Environmental Pollution (Series A) 24, 1-19.
- Knowles, S.C. and R.G. Zingmark (1978) Mercury and temperature interactions on the growth rates of three species of freshwater phytoplankton. Journal of Phycology 14, 104-109.
- Kohn, G.K. (1980) Bioassay as a monitoring tool. Residue Reviews 76, 99-129.

- Kuiper, J. (1981) Fate and effects of mercury in marine plankton communities in an experimental enclosure. Ecotoxicology and Environmental Safety 5, 106-134.
- Kuhnhold, W.W. (1978) Impact of the Argo Merchant oil spill on macrobenthic and pelagic organisms. pp. 153-179, in The Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills. American Institute of Biological Sciences. Washington, D.C.
- Lee, W.Y., K.Winters, and J.A.C. Nicol (1978) The biological effects of the water soluble fractions of a No. 2 fuel oil on the planktonic shrimp Lucifer faxoni. Environmental Pollution 15, 167-183.
- Li, W.K.W. (1980) Cellular accumulation and distribution of cadmium in Isochrysis galbana during growth inhibition and recovery. Journal of Plankton Research 2, 283-294.
- Linden, E., B-E. Bengtsson, O. Svanberg, and G. Sundstrom (1979) The acute toxicity of 78 chemicals and pesticide formulations against the bleak (Alburnus alburnus) and the harpacticoid Nitocra spinipes. Chemosphere 11/12, 843-551.
- Linden, O. (1975) Acute effects of oil and oil/dispersant mixture on larvae of Baltic herring. Ambio 4, 130-133.
- Lonning, S. and B.E. Hagstrom (1975a) The effect of crude oils and the dispersant Corexit 8666 on sea urchin gametes and embryos. Norwegian Journal of Zoology 23, 121-129.
- Lonning, S. and B.S. Hagstrom (1975b) The effects of oil dispersants on the cell in fertilization and development. Norwegian Journal of Zoology 23, 131-134.

- Macek, K.J. and B.H. Sleight, III (1977) Utility of toxicity tests with embryos and fry of fish in evaluating hazards associated with the chronic toxicity of chemicals to fishes. pp 137-146, in Aquatic Toxicology and Hazard Evaluation, F.L. Mayer and J.L. Hamelink, eds. American Society for Testing and Materials, Philadelphia. 307 pp.
- MacInnes, J.R. and A. Calabrese (1979) Combined effects of salinity, temperature, and copper on embryos and early larvae on the American oyster, Crassostrea virginica. Archives of Environmental Contamination and Toxicology 8, 553-562.
- Macka, W., H. Wihlidal, G. Stahlik, J. Washuttl, and E. Bancher (1979) Uptake of $^{203}\text{Hg}^{++}$ and ^{115}Cd by Chlamydomonas reinhardtii under vario Chemosphere 10, 787-796.
- Maestrini, S.Y. and M-G. Kossut (1981) In situ cell depletion of some marine algae enclosed in dialysis sacs and their use for the determination of nutrient-limiting growth in Ligurian coastal water (Mediterranean Sea). Journal of Experimental Marine Biology and Ecology 50, 1-19.
- Majewski, H.S., J.F. Klaverkamp, and D.P. Scott (1978) Acute lethality and sub-lethal effects of acetone, ethanol, and propylene glycol on the cardiovascular and respiratory systems of rainbow trout. Water Research 12, 217-221.
- Maki, A.W. and W.E. Bishop (1979) Acute toxicity studies of surfactants to Daphnia magna and Daphnia pulex. Archives of Environmental Contamination and Toxicology 8, 599-612.
- Malanchuk, J.L. and G.K. Gruendling (1973) Toxicity of lead nitrate to algae. Water, Air, and Soil Pollution 2, 181-290.
- Margrey, S.L., D.J. Burton, and L.W. Hall, Jr. (1981) Seasonal temperature and power plant chlorination effects on estuarine invertebrates. Archives of Environmental Contamination and Toxicology 10, 691-703.

- Marshall, J.S. and D.L. Mellinger (1980) An in situ experimental method for toxicological studies on natural plankton communities. pp. 27-39, in Aquatic Toxicology, J.G. Eaton, P.R. Parrish, and A.C. Hendricks, eds. American Society for Testing and Materials, Philadelphia.
- Marsot, P., R. Fournier, and C. Blais (1981) Culture a dialyse: emploi de fibres creuses dialysantes pour la culture massive de phytoplancton. Canadian Journal of Fisheries and Aquatic Science 38, 905-911.
- McKim, J.M. (1977) Evaluation of tests with early life stages of fish for predicting long-term toxicity. Journal of the Fisheries Research Board of Canada 34, 1148-1154.
- Mileikovsky, S.A. (1970) The influence of pollution on pelagic larvae of bottom invertebrates in marine nearshore and estuarine waters. Marine Biology 6, 350-356.
- Mirkes, D.Z., W.B. Vernberg, and P.J. DeCoursey (1978) Effects of cadmium and mercury on the behavioral responses and development of Eurypanopeus depressus larvae. Marine Biology 47, 143-147.
- Mironov, O.G., and L.A. Lanskaya (1966) The influence of oil on the development of marine phytoplankton. Paper presented at the Second International Oceanographic Congress, Moscow, 1966. Cited from Corner (1978).
- Miura, T. and R.M. Takahashi (1973) Insect development inhibitors. 3. Effects on nontarget aquatic organisms. Journal of Economic Entomology 66, 917-932.
- Nemetz, P.N. and H.D. Drechsler (1978) The role of effluent monitoring in environmental control. Water, Air, and Soil Pollution 10, 477-497.
- Nimmo, D.R. Pesticides, in Principles of Aquatic Toxicology, J.M. Rand and S.R. Petrocelli, eds. Hemisphere Publishing. Franklinville, NY. (In press)

Nimmo, D.R., L.H. Bahner, R.A. Rigby, J.M. Sheppard, and A.J. Wilson, Jr.

(1977) Mysidopsis bahia: an estuarine species suitable for life-cycle toxicity tests to determine the effects of a pollutant. pp. 109-116, in Aquatic Toxicology and Hazard Evaluation, ASTM STP 634, F.C. Mayer and J.L. Hamelink, eds. American Society for Testing and Materials, Philadelphia.

Nimmo, D.R., T.L. Hamaker, E. Matthews, and J.C. Moore (1981) An overview of the acute and chronic effects of first and second generation pesticides on an estuarine mysid. pp. 3-19, in Biological Monitoring of Marine Pollution, F.J. Vernberg, A. Calabrese, F.T. Thurberg, and W.B. Vernberg, eds. Academic Press, New York.

Nimmo, D.R., T.L. Hamaker, J.C. Moore, and R.A. Wood (1980) Acute and chronic effects of Dimilin on survival and reproduction of Mysidopsis bahia. pp. 366-376, in Aquatic Toxicology, J.G. Eaton, P.R. Parrish, and A. C. Hendricks, eds. American Society for Testing and Materials, Philadelphia.

NOAA (1980) TSEIS oil spill. Report of the first year. Scientific Study (October 26, 1977 to December 1978). National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program Report, March 1980. National Oceanic and Atmospheric Administration, Boulder, Colorado.

O'Brien, W.J. and D. Kettle (1981) A zooplankton bioassay chamber for lab and field use. Journal of Plankton Research 3, 561-566.

Pankhurst, N.W., C.R. Boyden, and J.B. Wilson (1980) The effect of a fluoride effluent on marine organisms. Environmental Pollution (Series A) 23, 299-312.

Pankhurst, G.M., R.L. Overcast, and H.L. Bergman (1981) Toxicity of underground coal gasification condenser water and selected constituents to aquatic biota. Archives of Environmental Contamination and Toxicology 9, 543-555.

- Parsons, T.R., W.K. Li, and R. Waters (1976) Some preliminary observances on the enhancement of phytoplankton growth by low levels of mineral hydrocarbons. Hydrobiologia 51, 85-89.
- Pavicic, J. and T. Jarvenpaa (1974) Cadmium toxicity in adults and early larvae of the mussel Mytilus galloprovincialis Lam. pp. 179-188, in Comparative Studies of Food and Environmental Contamination, International Atomic Energy Agency. Vienna.
- Payne, A.G. and R.H. Hall (1979) A method for measuring algal toxicity and its application to the safety assessment of new chemicals. pp. 171-180, in Aquatic Toxicology, L.L. Marking and R.A. Kimerle, eds. American Society for Testing and Materials, Philadelphia.
- Pearce, J.B. (1980) The effects of pollution and the need for long-term monitoring. Helgolander Wissenschaftliche Meeresunters 34, 207-220.
- Pearson, T.H. and R. Rosenberg (1978) Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Annual Review of Oceanography and Marine Biology 16, 209-311.
- Pott, E. (1980) Die Hemmung der Futteraufnahme von Daphnia pulex-eine neue limnotopikologische Messgroesse. Zeitschrift fur Wasser Abwasserforschung 13, 52-54.
- Powers, C.D., R.G. Rowland, and C.F. Wurster (1977) Dieldrin induced destruction of marine algal cells with concomitant decrease in size of survivors and their progeny. Environmental Pollution 12, 17-25.
- Prahl, F.G. and R. Carpenter (1979) The role of zooplankton fecal pellets on the sedimentation of polycyclic aromatic hydrocarbons in Dabob Bay, Washington. Geochemica et Cosmochemica Acta 43, 1959-1972.

- Pulich, W.M. Jr., K. Winters, and C. Van Baalen (1974) The effects of No. 2 fuel oil and two crude oils on the growth and photosynthesis of microalgae. Marine Biology 28, 87-94.
- Rai, L.C., J.P. Gaur, and H.D. Kumar (1981) Protective effects of certain environmental factors on the toxicity of zinc, mercury, and methyl-mercury to Chlorella vulgaris. Environmental Research 25, 250-259.
- Ribeyre, F., A. Boudou, and A. Delarche (1981) Contamination of an experimental trophic chain by methyl mercury: importance of the primary production-consumption system. Environmental Pollution (Series A) 24, 193-206.
- Rice, D.W., Jr., and F.L. Harrison (1978) Copper sensitivity of Pacific herring, Clupea harengus pallasii, during its early life history. U.S. National Marine Fisheries Service Fisheries Bulletin 76, 347-356.
- Richardson, L.B., D.T. Burton, and J.C. Rhoderick (1981) Toxicity of bromate to striped bass ichthyoplankton (Morone saxatilis) and juvenile spot (Leiostomus xanthurus). Journal of Toxicology and Environmental Health 8, 687-695.
- Roderer, G. (1980) On the toxic effects of tetraethyl lead and its derivatives on the chrysophyte Poterioochromonas malhamensis. I Tetraethyl lead. Environmental Research 23, 371-384.
- Roderer, G. (1981) On the toxic effects of tetraethyl lead and its derivatives in the chrysophyte Poterioochromonas malhamensis. II Triethyl lead, diethyl lead and inorganic lead. Environmental Research 25, 361-371.
- Rosenberg, D.M., V.H. Resh, S.S. Balling, M.A. Barnby, J.N. Collins, D.V. Durbin, T.S. Flynn, D.D. Hart, G.A. Lamberti, E.P. McElravey, J.R. Wood, T.E. Blank, D.M. Schultz, D.L. Marrin, and D.G. Price (1981) Recent trends in environmental impact assessment. Canadian Journal of Fishery and Aquatic Science 38, 591-624.

- Rosenberg, R. (1972) Effects of chlorinated aliphatic hydrocarbons on larval and juvenile Balanus balanoides (L). Environmental Pollution 3, 313-318.
- Saboski, E.M. (1977) Effects of mercury and tin on frustular ultrastructure of the marine diatom, Nitzschia liebethrutti. Water, Air, and Soil Pollution 8, 461-466.
- Sakshaug, E. and A. Jensen (1978) The use of cage cultures in studies of the biochemistry and ecology of marine phytoplankton. Annual Review of Oceanography and Marine Biology 16, 81-106.
- Samain, J.F., J. Moal, A. Coum, R.R. Le Coz, and J.Y. Daniel (1980) Effects of the "Amoco Cadiz" oil spill on zooplankton. Helgolander Wissenschaftliche Meeresuntersuchungen 33, 225-235.
- Sanborn, H.R., and D.C. Malins (1977) Toxicity and metabolism of naphthalene: A study with marine larval invertebrates. Proceedings of the Society for Experimental Biology and Medicine 154, 151-155.
- Sanders, H.O., F.L. Mayer, Jr. and D.F. Walsh (1973) Toxicity, residue dynamics, and reproductive effects of phthalate esters in aquatic invertebrates. Environmental Research 6, 84-90.
- Sanders, J.G., J.H. Ryther, and J.H. Batchelder (1981) Effects of copper, chlorine, and thermal addition on the species composition of marine phytoplankton. Journal of Experimental Marine Biology and Ecology 49, 81-102.
- Schober, L.L. and W. Lampert (1976) Effects of sublethal concentrations of an herbicide on Daphnia. Die Naturwissenschaften 5, 241.
- Schober, L.L. and W. Lampert (1977) Effects of sublethal concentrations of the herbicide Atrazin in growth and reproduction of Daphnia pulex. Bulletin of Environmental Contamination and Toxicology 17, 269-277.

- Schultz, T.W., S.R. Freeman, and J.N. Dumont (1980) Uptake, depuration and distribution of selenium in Daphnia and its effects on survival and ultrastructure. Archives of Environmental Contamination and Toxicology 9, 23-40.
- Silverberg, B.A., P.T.S. Wong, and Y.K. Chau (1977) Effects of tetramethyl lead on freshwater green algae. Archives of Environmental Contamination and Toxicology 5, 305-313.
- Soto, C., J.A. Hellebust, and T.C. Hutchinson (1975a) Effect of naphthalene and aqueous crude oil extracts on the green flagellate Chlamydomonas angulosa. 1- Growth. Canadian Journal of Botany 53, 109-117.
- Soto, C., J.A. Hellebust, and J.C. Hutchinson (1975b) The effects of aqueous extracts of crude oils and naphthalene on the physiology and morphology of a freshwater green alga. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie 19, 2145-2154.
- Spehar, R.L., J.T. Fiandt, R.L. Anderson, and D.L. DeFoe (1980) Comparative toxicity of arsenic compounds and their accumulation in invertebrates and fish. Archives of Environmental Contamination and Toxicology 9, 53-63.
- Spencer, D.F. and R.W. Greene (1981) Effects of nickel on seven species of freshwater algae. Environmental Pollution (Series A) 25, 241-247.
- Spooner, M.F. and C.F. Corkett (1979) Effects of Kuwait oils on feeding rates of copepods. Marine Pollution Bulletin 10, 197-202.
- Steele, J.H., A.D. McIntyre, R. Johnston, I.G. Baxter, G. Topping, and H.D. Dooley (1973) Pollution studies in the Clyde Sea area. Marine Pollution Bulletin 4, 153-157.
- Stewart, J. (1977) Relative sensitivity to lead of a naked green flagellate, Dunaliella tertiolecta. Water, Air, and Soil Pollution 8, 243-247.

- Stillwell, E.F. and K.E. Corum (1982) Effects of cadmium and low magnesium on cell division and calcification in the marine coccolithophorid, Circosphaera (Hymenomonas) carterae. Marine Biology 66, 227-230.
- Stratton, G.W. and C.T. Corke (1979) The effects of cadmium ion on the growth, photosynthesis, and nitrogen activity of Anabaena inaequalis, Chemosphere 5, 277-282.
- Stratton, G.W., R.E. Burrell, M.L. Kurp, and C.T. Corke (1980) Interactions between the solvent acetone and the pyrethroid insecticide permethrin on activities of the blue-green alga Anabaena. Bulletin of Environmental Contamination and Toxicology. 24, 562-569.
- Stratton, G.W. and C.T. Corke (1981a) Interaction between acetone and two pesticides towards several unicellular green algae. Bulletin of Environmental Contamination and Toxicology 27, 13-16.
- Stratton, G.W. and C.T. Corke (1981b) Interaction of permethrin with Daphnia magna in the presence and absence of particulate matter. Environmental Pollution (Series A) 24, 135-144.
- Stuermer, D.H., R.B. Spies, and P.H. Davis (1981) Toxicity of Santa Barbara seep oil to starfish embryos: Part 1- Hydrocarbon consumption of test solutions and field samples. Estuarine Environmental Research 5, 275-286.
- Subba Rao, D.V. (1981a) Growth response of marine phytoplankters to selected concentrations of trace metals. Botanica Marina 24, 369-379.
- Subba Rao, D.V. (1981b) Effect of boron on primary production of nannoplankton. Canadian Journal of Fisheries and Marine Sciences 38, 52-58.
- Tagatz, M.E. and C.H. Deans. Comparison of field- and laboratory-developed estuarine benthic communities for toxicant-exposure studies. Water, Air, and Soil Pollution In press.

- Tagatz, M.E. and J.M. Ivey (1981) Effects of fenvalerate on field- and laboratory-developed estuarine benthic communities. Bulletin of Environmental Contamination and Toxicology 27, 256-267.
- Tagatz, M .E., J.M. Ivey, C.E. Dalbo, and J.L. Oglesby (1982) Responses of developing estuarine macrobenthic communities to drilling muds. Estuaries 5, 131-137.
- Tagatz, M.E., J.M. Ivey, N.R. Gregory, and J.L. Oglesby (1981) Effects of pentachlorophenol on field- and laboratory-developed estuarine benthic communities. Bulletin of Environmental Contamination and Toxicology 26, 137-143.
- Tagatz, M.E., J.M. Ivey, and H.K. Lehman (1979a) Effects of sevin on development of experimental estuarine communities. Journal of Toxicology and Environmental Health 5, 643-651.
- Tagatz, M.E., J.M. Ivey, H.K. Lehman, and J.L. Oglesby (1978a) Effects of a lignosulfonate-type drilling mud on development of experimental estuarine macrobenthic communities. Northeast Gulf Science 2, 35-42.
- Tagatz, M.E., J.M. Ivey, J.C. Moore, and M. Tobia (1977) Effects of pentachlorophenol on the development of estuarine communities. Journal of Toxicity and Environmental Health 3, 501-506.
- Tagatz, M.E., J.M. Ivey, and J.L. Oglesby (1979b) Toxicity of drilling mud biocides to developing estuarine macrobenthic communities. Northeast Gulf Science 3, 88-95.
- Tagatz, M.E., J.M. Ivey, and M. Tobia (1978b) Effects of Dowicide G-ST on development of experimental estuarine macrobenthic communities. pp. 157-163, in Pentachlorophenol, K. Ranga Rao, ed. Plenum Publishing Corp., New York.

- Tagatz, M.E. and M. Tobia (1978) Effect of barite ($BaSO_4$) on development of estuarine communities. Estuarine and Coastal Marine Science 7, 401-407.
- Thomas, W.H., J.T. Hollibaugh, and D.L.R. Seibert (1980) Effects of heavy metals on the morphology of some marine phytoplankton. Phycologia 19, 202-209.
- Truhaut, R., J.F. Ferard, and J.M. Jouany (1980) Cadmium EC₅₀ determinations on Chlorella vulgaris involving different parameters. Ecotoxicology and Environmental Safety 4, 215-223.
- Vighi, M (1981) Lead uptake and release in an experimental trophic chain. Ecotoxicology and Environmental Safety 5, 177-193.
- Walsh, G.E. (1972) Insecticides, herbicides, and polychlorinated biphenyls in estuaries. Journal of the Washington Academy of Science 62, 122-139.
- Walsh, G.E. (1978) Toxic effects of pollutants on plankton. pp. 257-274, in Principles of Ecotoxicology, G.C. Butler, ed. John Wiley and Sons, New York.
- Walsh, G.E. Algal bioassays of industrial and energy process effluents. in, Algae as Ecological Indicators, L.E. Shugart, ed. Academic Press, New York (In press a).
- Walsh, G.E. Cell death and inhibition of population growth of marine unicellular algae by pesticides. Aquatic Toxicology (In press b).
- Walsh, G.E., K. Ainsworth, A.J. Wilson, Jr. (1977) Toxicity and uptake of kepone in marine unicellular algae. Chesapeake Science 18, 222-223.
- Walsh, G.E. and S.V. Alexander (1980) A marine algal bioassay method: results with pesticides and industrial wastes. Water, Air, and Soil Pollution 13, 45-55.

- Walsh, G.E., L.H. Bahner, and W.B. Horning (1980) Toxicity of textile mill effluents to freshwater and estuarine algae, crustaceans and fishes. Environmental Pollution (Series A) 21, 169-179.
- Walsh, G.E., K.M. Duke, and R.B. Foster (1982) Algae and crustaceans as indicators of bioactivity of industrial wastes. Water Research 16, 879-883.
- Ware, G.W. (1980) Effects of pesticides on nontarget organisms. Residue Reviews 76, 173-201.
- Ward, G.S. and P.R. Parrish (1980) Evaluation of early life stage toxicity tests with embryos and juveniles of sheepshead minnows (Cyprinodon variegatus). pp. 243-247, in Aquatic Toxicology, J.G. Eaton, P.R. Parrish, and A.C. Hendricks, eds. American Society for Testing and Materials, Philadelphia.
- Wells, P.G. (1972) Influence of Venezuelan crude oil on lobster larvae. Marine Pollution Bulletin 3, 105-106.
- Westernhagen, H.V., J. Dethlefsen, and H. Rosenthal (1979) Combined effects of cadmium, copper, and lead on developing herring eggs and larvae. Helgolander Wissenschaftliche Meeresuntersuchungen 32, 257-278.
- Wilkfors, G.H. and R. Ukeles (1982) Growth and adaptation of estuarine unicellular algae in media with excess copper, cadmium, or zinc, and effects of metal-contaminated algae food on Crassostrea virginica larvae. Marine Ecology-- Progress Series 7, 191-206.
- Winner, R.W. (1981) A comparison of body length, brood size, and longevity as indices of chronic copper and zinc stresses in Daphnia magna. Environmental Pollution (Series A) 26, 33-37.

- Winner, R.W., T. Keeling, R. Yeager, and M.P. Farrell (1977) Effect of food type on the acute and chronic toxicity of copper to Daphnia magna. Freshwater Biology 7, 343-349.
- Winters, K., C. Van Baalen, and J.A.C. Nicol (1977) Water soluble extractives from petroleum oil: chemical characterization and effects on microalgae and marine animals. Rapports et Proces-Verbaux des Reunions Conseil International pour Exploration de la Mer, 171, 166-174.
- Wisely, B. and R.A.P. Blick (1967) Mortality of marine invertebrates larvae in mercury, copper, and zinc solutions. Australian Journal of Marine and Freshwater Research 18, 63-37.
- Woolery, M.L. and R.A. Lewin (1976) The effects of lead on algae. IV. Effects on respiration and photosynthesis of Phaeodactylum tricornutum, (Bacillariophyceae). Water, Air, and Soil Pollution 6, 25-37.
- Yan, N.D. and R. Strus (1980) Crustacean zooplankton communities of acidic lakes near Sudbury Ontario. Canadian Journal of Fisheries and Aquatic Sciences 37, 2282-2293.